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Implementation of a Network -Level Pavement Structural Condition Index based on Falling Weight Deflectometer Data

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Implementation of a Network -Level Pavement Structural Condition Index based on Falling Weight Deflectometer Data

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December, 2010

Acknowledgments

I would like to take this opportunity to thank my advisor, Dr. Zhanmin Zhang. His constant guidance and systematic approach of dealing with things has helped me during my master's studies. I would also like to express sincere gratitude to Dr. Michael R Murphy for his support. In spite of his busy schedules, Dr. Murphy always had the time to clear my problems regarding the research. Thanks to Lu and Hui for their suggestions and guidance. My special thanks to my friends, Prasad and Abdus, for helping in many ways. I would like to thank my family for providing me with background and support to deal with ups and downs of life. Finally, I would like to thank Ram, my husband, for his wonderful love, support and understanding through the duration of my study.

December 3, 2010

Abstract

Implementation of a Network -Level Pavement Structural Condition Index based on Falling Weight Deflectometer Data

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The University of Texas at Austin, 2010

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The Texas Department of Transportation (TxDOT) uses the Pavement Management Information Systems (PMIS) to store and analyze pavement data, and to summarize information needed to support pavement-related decisions. The information on overall condition of the pavement is stored in PMIS, measured with various scores based on visual distress and ride quality surveys. However, a direct measure of the pavement structural condition is currently not in use. A network-level index that can distinguish pavements that require Preventive Maintenance (PM) from those that require Rehabilitation (Rhb) is required, because, it is not cost-effective to apply PM treatments to pavements that are structurally inadequate. The necessity to use an index to improve pavement treatment selection process, especially under financial constraints has motivated this research. The objective of this research is to validate the pavement Structural Condition Index (SCI) developed under a previous Research Project 0-4322, and to develop guidelines for implementing the SCI at the network level.

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Chapter 1: Introduction

1.1 BACKGROUND

Texas has the largest state-maintained highway system in the United States, with over 195,000 highway lane-miles. The Texas Department of Transportation (TxDOT) uses the Pavement Management Information Systems (PMIS) to store, retrieve and analyze pavement data, and prepare reports that summarize information needed to support pavement-related decisions [TxDOT 1994]. The information on condition of the pavement is stored in PMIS, measured with various scores based on visual distress and ride quality surveys. These PMIS scores help in identifying the funding needs required for pavement Maintenance and Rehabilitation (M&R) activities.

The current funding situation for pavement infrastructure management is becoming increasingly limited due to factors such as construction cost inflation and reduced fuel tax revenue. The available funding will not be able to address all the pavement management needs, resulting in an impact at both economic (bad pavements increase fuel consumption and maintenance costs) and community (shift of business centers based on the pavement infrastructure condition) levels.

The current statewide goal for pavement condition, set by the Texas Transportation Commission in 2002, is to achieve 90 percent of the state-maintained lane miles in “good” or better condition by 2012. However, a recent study concluded that the current funding required for achieving and maintaining this goal is insufficient and that the pavement infrastructure condition will deteriorate to unacceptable levels [Zhang

2009]. In this study, the analysis was conducted based on the funding allocation for FY 2009 from the 4-year Pavement Management Plans, and funding projection for FY 2010-2035 developed by TxDOT. The predicted pavement performance trend for FY 2009-2030, from this analysis, is shown in Figure 1.1. Hence, under financial constraints, there is a need for a cost-effective pavement treatment selection process.

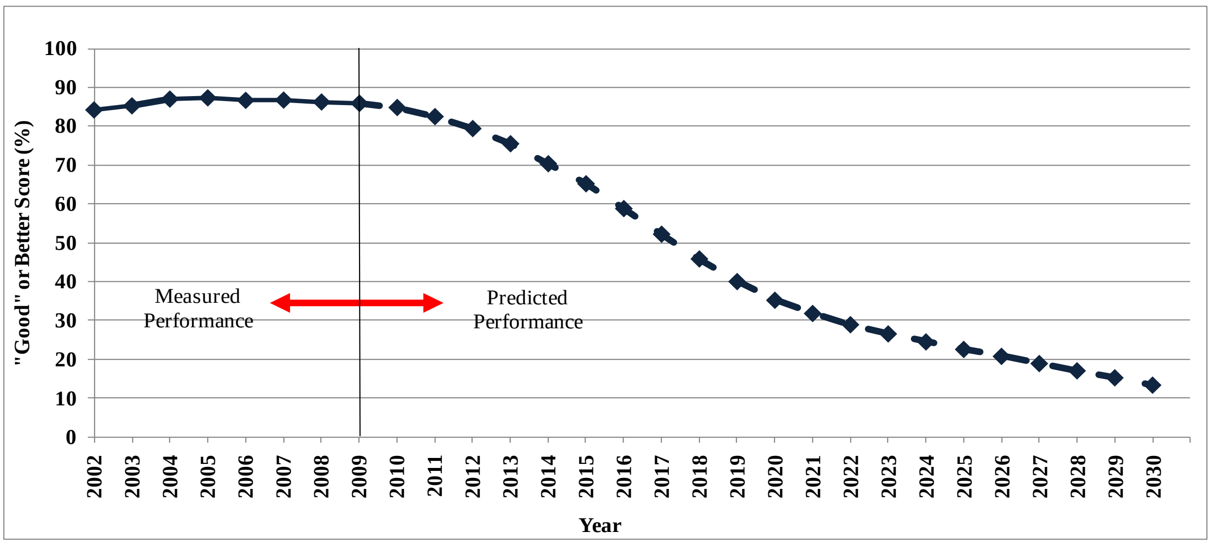


Figure 1.1 Predicted Pavement Performance Trend for FY 2009 – 2030 [Zhang 2009]

The current PMIS scores provide a good indication of the overall pavement condition. However, a direct measure of the pavement structural condition is currently not in use. A network-level index that can distinguish pavements that require Preventive Maintenance (PM) from those that require Rehabilitation (Rhb) is required, because, it is not cost-effective to apply PM treatments to pavements that are structurally inadequate. Thus, the necessity to use an index to improve pavement treatment selection process under budget constraints has motivated this research. The objective of this research is to validate the pavement Structural Condition Index (SCI) developed under a previous research project conducted by CTR, (Project 0-4322) [Zhang 2003] and to develop guidelines for implementing the SCI at the network level.

1.2 THESIS OBJECTIVE

The main objective of this research is to validate the SCI with pavement sections representing a broad range of pavement conditions and climatic regions of the state, and to prepare the necessary materials to assist TxDOT with implementation of the SCI. During the course of the research, some districts were selected in coordination with the research Project Director, from which the necessary data was collected. More specifically, the objectives of this research are:

- To validate the Structural Condition Index (SCI) method;
- To determine the effect of bedrock depth on the SCI values;
- To determine the representative SCI value of a pavement section;
- To develop guidelines about the M&R treatment category, based on the representative SCI value of a pavement section; and
- To determine the ideal FWD testing spacing, for adequately characterizing the pavement structural condition using SCI, at the network level.

1.3 THESIS SCOPE

The Texas State highway system has ninety-four percent of its total mileage as flexible pavements and the rest six percent as rigid pavements. This research focuses on evaluation of the SCI method for flexible pavements (asphalt concrete or thin surface-treated) in Texas. However, the SCI method has not yet been modified and evaluated for use on rigid pavements (portland cement concrete) in this research.

1.4 THESIS ORGANIZATION

The thesis is organized into eight chapters. Chapter 1 presents the introduction, objectives and organization. Chapter 2 focuses on the state-of-the-art in network-level structural condition assessment. Chapter 3 discusses the data and data sources used for the research. Chapter 4 describes the validation process of the SCI and the effect of bedrock depth on SCI values. Chapter 5 discusses methods for determining the representative SCI value of a section. Chapter 6 summarizes the survey results conducted with the TxDOT for SCI threshold analysis. Chapter 7 provides a recommendation for the necessary spacing of the FWD test points, to characterize pavement structural condition using SCI at the network level. Finally, Chapter 8 provides conclusions and recommendations for this research.

Chapter 2: An Overview of the State -of- the-Art of Structural Indices for Network-Level Applications

2.1 INTRODUCTION TO THE STRUCTURAL CONDITION INDEX

The structural condition of a pavement section can be assessed through non-destructive methods such as deflection testing using the Falling Weight Deflectometer (FWD). The back-calculation of the subgrade and the pavement layer moduli is one of the procedures commonly used to characterize the structural condition of a pavement using the FWD data. However, at present, the TxDOT PMIS does not have the pavement layer thickness information which is required for the back-calculation procedure [TxDOT 2000]. The TxDOT PMIS stores a structural screening index called the Structural Strength Index (SSI) which is based on the FWD data [Scullion 1998]. Though the SSI does not require the pavement layer thickness information, internal studies by the TxDOT indicated that the SSI was not sensitive enough to discriminate pavements that need structural reinforcement from those that do not [TxDOT 2000].

This shortcoming of the SSI led to the development of a new methodology called the Structural Condition Index (SCI), using FWD data, under a previous research (Project 0-4322) [Zhang 2003]. The SCI is the ratio of the 'existing/effective' AASHTO Structural Number (SN_{eff}) determined from both the FWD measurements and the total pavement thickness [AASHTO 1986], and the 'required' AASHTO Structural Number (SN_{req}) based on the estimated 20-year Equivalent Single Axle Loads (ESALs) for the route, and the subgrade modulus (M_R) [AASHTO 1993].

2.2 OBJECTIVE OF THE LITERATURE REVIEW

The Structural Condition Index (SCI) methodology was developed more than six years ago [Zhang 2003]. Hence, it is important to look into the latest advancements in this area. A review of the structural indices for network-level applications must be undertaken, and such indices, if identified, should be evaluated along with the SCI. Hence, in this research, the literature review was focused on relevant material/previous research to identify structural indices that were developed to evaluate pavements at the network level.

2.3 SUMMARY OF THE NETWORK-LEVEL STRUCTURAL INDICES

The review was not limited to the United States alone but also included methods developed by other countries. Table 2.1 summarizes the methods developed by the different agencies; including each agency's objective, concept, approach and conclusions.

Table 2.1 Agency Objective, Concept, Approach and Conclusions

Agency	Objective	Concept	Approach	Conclusions
Oklahoma DOT [Williams 2006]	To determine the Structural Capacity of the primary arterial system.	FWD and Ground Penetrating Radar (GPR) profiles were used to identify the changes in the pavement structure.	GPR results were used to obtain the layer thickness estimates for use in FWD back-calculation of the layer moduli.	SN, M_R were used to determine the structural capacity. GPR was found to be effective only for certain pavement structures.
New Jersey DOT [Sameh 2004]	To develop Structural Adequacy Index (SAI) model so as to identify current & future structural needs and to prioritize the needs.	SAI = f (SNR) SNR (Structural Number Ratio) =	Layer thickness estimates were obtained from GPR or coring data. $SN_{eff} = f$ (FWD data) $SN_{req} = f$ (Future Traffic) $SN_{asbuilt} = f$ (AASHTO layer coefficients eq.)	Results obtained from SAI= f (SNR) were used to prioritize the needs. Proposed SAI model is based on judgment & local experience.
Kansas DOT [Mustaque 2000]	To determine the structural capacity of pavements at the network level.	Used regression for determining ΔSN (decrease in SN) ΔSN = f (time since pavement's last rehab, tot. pave thickness)	SN was calculated using FWD data which was then correlated with factors like the tot. pave thickness)	ΔSN gives the deterioration of the structural capacity at the network level. Study was limited only to 357 miles of non-interstate pavements.

Table 2.1 (continued)

Virginia DOT [Brian 2008]	Use the results from FWD network-level survey to develop index, as a condition forecasting tool.	FWD data was analyzed by calculating M_R, SN_{eff}.	Analysis was done in accordance with the AASHTO design guide.	The index could not be developed in the study due to limitations in the traffic data.
Indiana DOT [Noureldin 2005]	To investigate employing FWD & GPR in pavement evaluation at the network level.	Layer modulus was determined through the FWD deflections. Layer thickness was estimated from the GPR readings.	Remaining Service Life (RSL) in terms of ESALs was estimated through the central FWD deflection (W_1)	Employing GPR at the network level is a cumbersome task.
European Cooperation in Science & Technology (COST) [Thierry 2008]	To identify badly performing sections at the network level by developing a Global Performance Indicator.	Global Performance Indicator was developed by grouping of Single Performance Indices into Combined such as Structural, Environmental and Functional Performance Indices.	Structural Index was determined by Surface Curvature Index (W_1-W_2 sensor deflections)	This index is measured from 0 (good condition) to 5 (poor condition). This model takes only the current pavement condition into account.
South Africa CSIR [Horak 2008]	Benchmarking methodology using the deflection bowl parameters along with visual survey has been proposed in this study.	Used deflection bowl parameters: Base Layer Index (BLI), Middle Layer Index (MLI) & Lower Layer Index (LLI), and assigned them	BLI= W_1-W_2 (sensor deflections) MLI= W_2-W_3 (sensor deflections)	Pavement layer thickness information is not required. However, information about base type is required.

Table 2.1 (continued)

		as sound, warning and severe based on the range of each parameter.	LLI= W_3-W_4 (sensor deflections)	
Australia [Binod 2003]	Western Australia experience in the usage of FWD at the network level survey.	Central FWD deflection data and Surface Curvature Index were used as the pavement strength indicators.	FWD deflections were used to compute the Surface Curvature Index. (W_1-W_2)	This method considers only the current structural condition of the pavement.
Saudi Arabia [Abdullah 1999]	Pavement data collection and evaluation on the main street Riyadh network.	Central FWD deflection data was used as an indicator of pavement structural capacity.	The central FWD Deflection data was used in the analysis (W_1)	This method is simple. However, this method does not consider the future needs of the pavement structure.
Simple Model [Pradeep 2006]	To develop a simple and cost effective model for structural evaluation of pavements at the network level.	This study's Structural Condition Index (SCI) was based on the cumulative damage principle of Miner. —	Used rutting and cracking data obtained from the LTPP database, to correlate with the SCI.	This model is based on the detailed project level visual distress survey results.
South Carolina DOT [Baus 2001]	To assess the feasibility of deflection based Structural Adequacy Index (SAI) in the SCDOT PMS.	SAI = f (ER) *ER= ESALs ratio* $ER = \overline{}$	SN, M_R = f (FWD data) $ESAL_c$ = Cumulative ESALs at the time of FWD testing $ESAL_f$=f	Necessary changes to the SAI model can be made, only after a pilot program implementation, which has not yet been done.

Table 2.1 (continued)

			(AASHTO design equation using SN & M_R)	
Ohio DOT [FHWA/OH 2007/05]	To improve decisions based on the structural adequacy of the pavement.	Pavement service life (RSL) was related based on the SHRP test results.	-Report NA-	-Report NA-

2.4 SUMMARY

The literature review suggested that most of the agencies adopted either the Falling Weight Deflectometer (FWD) or the Ground Penetrating Radar (GPR) for the structural evaluation of pavements at the network level. However, there are certain challenges associated with using GPR and FWD at the network level. Considering the size of Texas, evaluating pavement structural conditions with GPR and/or FWD data at the network level requires personnel, traffic control, and other resources, resulting in high data collection costs. Moreover, Texas does not have an automated GPR data analysis software system, making GPR data interpretation completely dependent on human experts. As for the evaluation methods, although several methods developed and employed by some agencies were examined, no new structural indices or new information was obtained that could be used to improve the SCI method.

Chapter 3: Data and Data Sources

3.1 INTRODUCTION

This chapter describes the data collection activities undertaken for this research, including discussions on the collected data and supporting documents from the TxDOT. More specifically, the following data was collected from TxDOT:

- Falling Weight Deflectometer (FWD) data along with Texas Reference Markers (TRM);
- Construction plan sheets showing both the project location and typical sections;
- Ground Penetrating Radar (GPR) data (if available);
- Dynamic Cone Penetrometer (DCP) data (if available);
- Photographs of pavement conditions taken during data collection (if available);
- Core data with laboratory thickness measurement records (if available);
- Project-level pavement design documents (if available);
- Load Zone Removal Request forms R1084 (if available); and
- Project-level traffic data.

TxDOT provided the project-level FWD data for 350 pavement sections. All FWD data was collected using the standard 12" sensor spacing used in Texas for flexible pavement testing. However, obtaining the layer thickness information and other supporting data for all the sections was not feasible due to time constraints. Hence, a total of 180 pavement sections were used for this research. The obtained data was reviewed and any additional data needed for the Structural Condition Index (SCI) analysis was requested. The framework used for the data collection and processing is illustrated in Figure 3.1. The data for each pavement section was stored in a separate excel workbook. The typical data stored for each pavement section is given in Table 3.1.

Table 3.1 Typical data stored for each pavement section in the spreadsheet

<table>
<tr><th>Data Item</th><th>Example</th></tr>
<tr><td>District</td><td>Austin</td></tr>
<tr><td>County</td><td>Williamson</td></tr>
<tr><td>Environmental Zone</td><td>Mixed</td></tr>
<tr><td>Route</td><td>SH 195</td></tr>
<tr><td>Beginning and Ending TRM</td><td>TRM 416-0.921 to TRM 412+0.851</td></tr>
<tr><td>Section length (miles)</td><td>5.921</td></tr>
<tr><td>Average Daily Traffic (ADT)</td><td>10,500</td></tr>
<tr><td>Estimated 20-year ESALs</td><td>10,385,000</td></tr>
<tr><td>Pavement layer thickness (inches)</td><td>1.5” Asphalt Concrete (AC) surface; and
9” Flexible Base</td></tr>
<tr><td>Average bedrock depth (inches)</td><td>72”</td></tr>
<tr><td>FWD data</td><td>
<table>
<tr><th rowspan="3">TRM</th><th></th><th></th><th colspan="7">Deflection in Mils</th></tr>
<tr><th>Station</th><th>Load (lb)</th><th>0"</th><th>12"</th><th>24"</th><th>36"</th><th>48"</th><th>60"</th><th>72"</th></tr>
<tr><th></th><th></th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W5</th><th>W6</th><th>W7</th></tr>
<tr><td></td><td>0</td><td>10,550</td><td>3.8</td><td>3.22</td><td>2.69</td><td>2.15</td><td>1.66</td><td>1.28</td><td>0.91</td></tr>
<tr><td></td><td>0.198</td><td>10,538</td><td>3.22</td><td>2.56</td><td>2.15</td><td>1.78</td><td>1.37</td><td>1.07</td><td>0.79</td></tr>
<tr><td>416+0.50</td><td>0.394</td><td>10,264</td><td>3.54</td><td>3.15</td><td>2.42</td><td>1.77</td><td>1.39</td><td>1.04</td><td>0.72</td></tr>
<tr><td></td><td>0.558</td><td>10,308</td><td>4.43</td><td>3.83</td><td>3.05</td><td>2.43</td><td>1.88</td><td>1.47</td><td>1.09</td></tr>
<tr><td></td><td>0.811</td><td>10,387</td><td>3.69</td><td>3.05</td><td>2.56</td><td>2.06</td><td>1.61</td><td>1.19</td><td>0.81</td></tr>
<tr><td>416+00</td><td>0.921</td><td>10,435</td><td>4.67</td><td>4.27</td><td>3.95</td><td>1.84</td><td>1.46</td><td>1.19</td><td>0.94</td></tr>
<tr><td></td><td>1.213</td><td>10,479</td><td>2.97</td><td>2.3</td><td>1.82</td><td>1.39</td><td>1.07</td><td>0.8</td><td>0.6</td></tr>
<tr><td>414+1.5</td><td>1.433</td><td>10,486</td><td>2.66</td><td>2.09</td><td>1.55</td><td>1.2</td><td>0.88</td><td>0.65</td><td>0.44</td></tr>
</table>
</td></tr>
<tr><td>Back-calculated modulus (ksi)</td><td>
<table>
<tr><th colspan="4">BACK-CALCULATED MODULUS (ksi)</th></tr>
<tr><th>TRM</th><th>Surface</th><th>Base</th><th>Subgrade</th></tr>
<tr><td></td><td>372.3</td><td>41.7</td><td>9</td></tr>
<tr><td></td><td>140</td><td>10</td><td>4.4</td></tr>
<tr><td>TRM 416+0.50</td><td>554</td><td>75.6</td><td>7.5</td></tr>
</table>
</td></tr>
<tr><td>PMIS scores</td><td>Ride, Distress and Condition scores</td></tr>
</table>

The total pavement thickness information, considered to be ‘better material’ placed and compacted above the natural or prepared subgrade, is used as an input in the SCI method. In this research, the pavement layers consisting of a bituminous surface (single or multiple layers), untreated flexible base, stabilized base, stabilized subgrade, recycled paving material, and, scarified and re-compacted, existing paving materials were considered to be part of the total pavement thickness.

The actual bedrock depth measurements, using an auger or similar device, were not available in this research. Hence, the bedrock depth measurement was obtained from the calculated rigid layer depth estimate which is provided as a part of the MODULUS program output [Rohde 1990]. The average bedrock depth was thus based on an assessment of the calculated rigid layer depth values associated with each FWD test point.

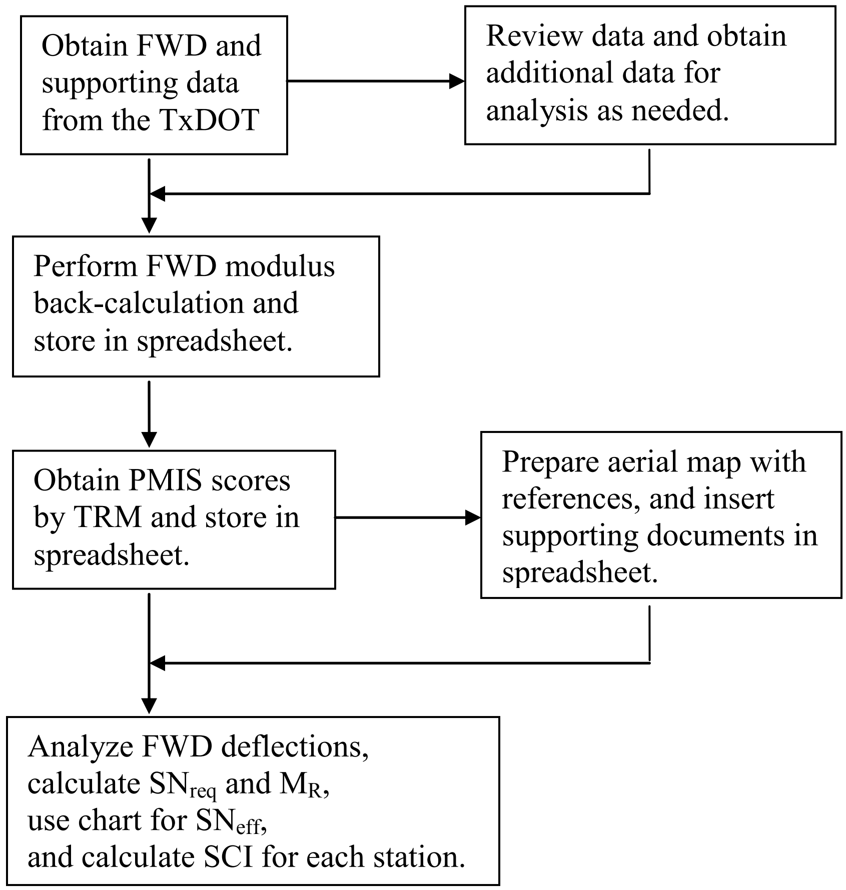


Figure 3.1 Framework used for data collection and processing

3.2 FACTORS CONSIDERED IN DATA PREPARATION

The data preparation started with the categorization of factors such as pavement subgrade modulus (M_R), estimated 20-year Equivalent Single Axle Loads (ESALs) and environmental zones in order to develop a matrix chart.

3.2.1 Matrix Chart

One of the primary objectives of this research is to validate the Structural Condition Index (SCI) method. For the validation exercise, inputs that define a section such as subgrade modulus, estimated 20-year ESALs and environmental zones play an important role. Texas is a large state and as such, pavement designs and materials vary significantly across the state, making the above three inputs more critical. As an example, all other factors being equal, a pavement in the wet-cold region of Texas would be expected to have higher seasonal deflections on average than a pavement in the dry-warm region of Texas, due to subgrade moisture conditions. Hence, a matrix chart, shown in Appendix A, was created which helps in ensuring that all primary factors that could potentially affect SCI calculations have been taken into consideration during the validation, an important step for determining the effectiveness of SCI.

The matrix chart is developed based on these key factors: Texas environmental zones, average subgrade modulus and estimated 20-year ESALs. These factors were chosen based on Texas' conditions that are known or expected to affect pavement structural condition and/or deflection values. Each factor was further subdivided into different categories and is discussed in the later part of the chapter. The matrix chart shows the data for the 180 pavement sections assigned to their respective cells, based on the factor level criteria, established for each of these categories. Thus, each cell in the chart represents a unique combination of factors that helps categorize a section.

3.2.1.1 Environmental Zones

Texas encompasses a broad range of climatic conditions. Figure 3.2 shows the environmental zones used in the study, which are defined by temperature and rainfall conditions. These zones were established based on the observation of similar seasonal deflection patterns under specific climatic conditions in each zone [Scullion 1988]. The information about Texas districts (district name abbreviations in Figure 3.2) are posted on the TxDOT website [http://www.dot.state.tx.us/local_information/, Accessed November 2010].

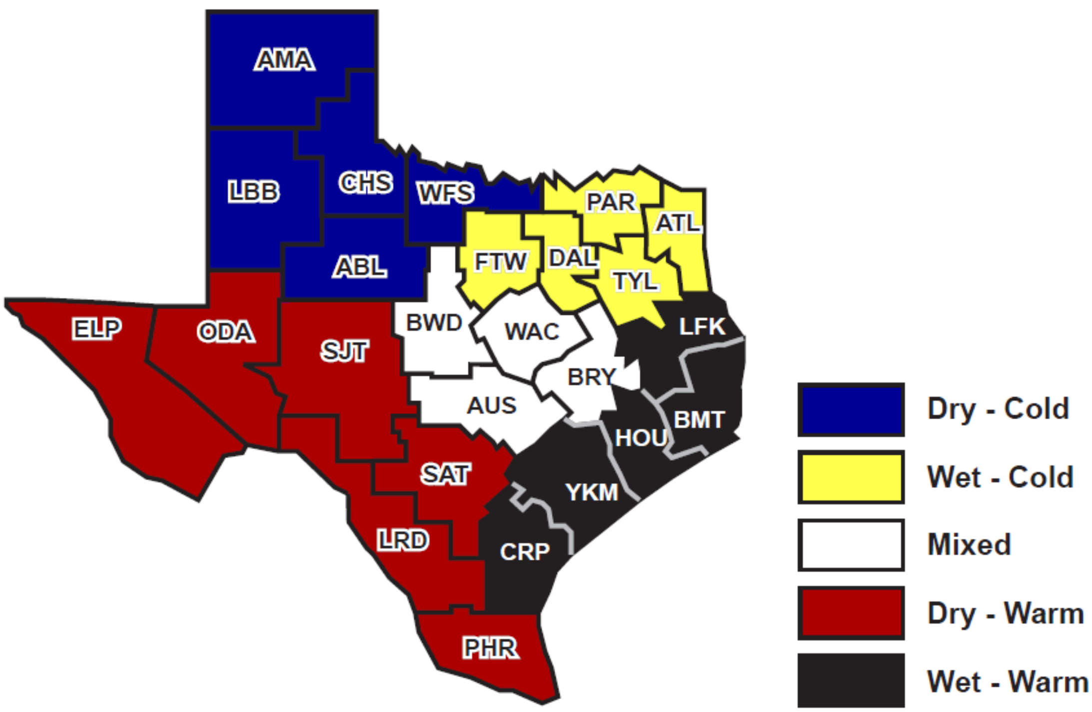


Figure 3.2 Texas Environmental Zones

3.2.1.2 Subgrade Categories

Pavement subgrade is a major factor in determining the pavement's performance. In the previous research (Project 0-4322), the subgrade modulus values defined in psi, were assigned to three categories as low (1,000-5,400), medium (5,400-7,500) and high (7,500-40,000). However, during the process of implementation, the subgrade limits have been re-adjusted according to Texas' conditions. Discussions with the research Project Director resulted in a greater range of subgrade stiffness categories based on the back-calculated subgrade moduli values. The subgrade designations were assigned to the following five subgrade stiffness ranges as given in Table 3.2.

Table 3.2 Subgrade Categories

Category	Subgrade (psi)
Very Poor (VP)	< 6,000
Poor (P)	6,000 - 10,000
Fair (F)	10,001 – 14,000
Good (G)	14,001 – 18,000
Very Good (VG)	> 18,000

3.2.1.3 Traffic Categories

The estimated 20-year ESALs is one of the inputs in the SCI analysis. For this research, the estimated 20-year ESALs stratification included five categories as shown in Table 3.3. Based on Texas' conditions and engineering judgment, the "Very Low" category generally includes the low-volume Farm to Market (FM) roads with low

Average Daily Traffic (ADT) and few trucks. The "Low" category includes the higher-volume FM roads and the lower-volume State Highway (SH) routes. The "Medium" category includes FM, SH and US Highways (US) routes with high ADT and moderate truck volumes. The "High" and "Very High" categories include very high-volume routes with high truck traffic which usually exceeds 750 trucks per day [Murphy 2010].

Table 3.3 Traffic Categories

Category	Traffic (ESALs)
Very Low	< 1,000,000
Low	1,000,000 - 3,000,000
Medium	3,000,000 - 10,000,000
High	10,000,000 - 30,000,000
Very High	> 30,000,000

3.2.1.4 Bedrock Depth Categories

The SCI calculations are dependent on the FWD data. Large FWD deflections at the seventh sensor (W_7) location (72" from the load plate) are usually related to a weaker subgrade. However, based on experience with Texas conditions, low W_7 values may either be due to a strong subgrade or could be a weak subgrade over relatively shallow bedrock. Though the matrix chart is not based on the bedrock depth categories, to find the effect of shallow bedrock on the SCI values with in-service pavements, it was decided to stratify bedrock depth categories as shown in Table 3.4. These categories were established based on engineering experience and other studies which have shown the effects of shallow bedrock on FWD deflections [Rohde 1994]. The "Variable" category was established for pavement sections that encompassed both the shallow and the deep bedrock along a route.

Table 3.4 Bedrock Depth Categories

Category	Bedrock Depth (inches)
Very Shallow	<60
Shallow	60-100
Moderate	100-140
Deep	140-180
Very Deep	>180
Variable	Shallow & Deep Sections

3.3 DATA SOURCES AND DATA UTILIZATION

The data was collected from TxDOT for the SCI analysis. The details of the aspects considered during the data collection along with the utilization of the data are summarized in this section.

3.3.1 FWD Data

The FWD data for the 180 sections was obtained from different projects, including forensic investigations, super-heavy load analyses, load zone roadway analyses, project-level pavement design projects, and data collected for other research projects. The number of pavement sections with available FWD data in each environmental zone is shown in Figure 3.3.

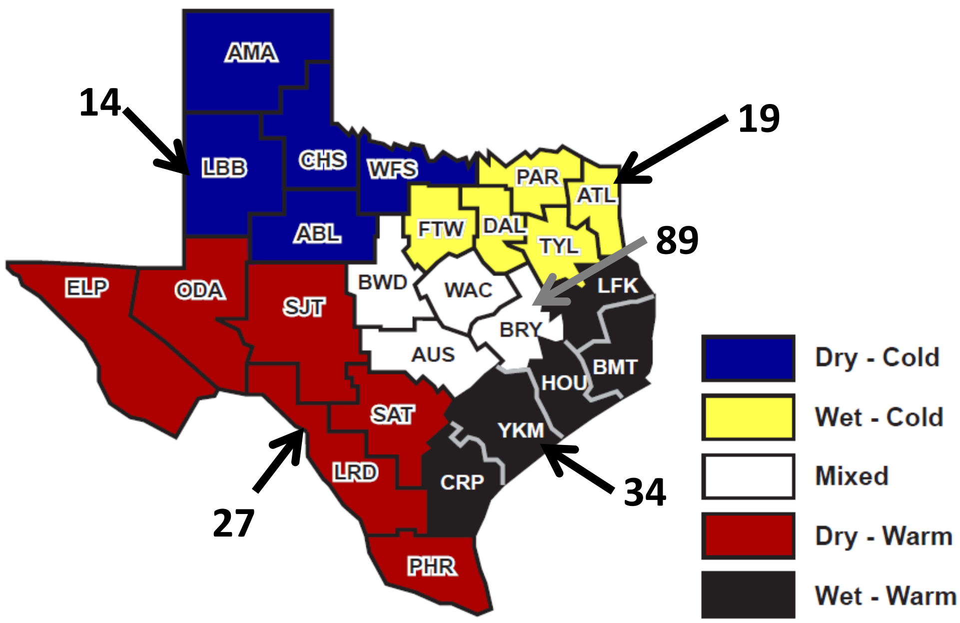


Figure 3.3 Number of pavement sections with available FWD data in each environmental zone

Most of the FWD data was collected between 1998 and 2009 during any given month of the year. The interval at which the FWD data was collected varied from section to section depending on the purpose of testing. For some projects, FWD measurements were recorded for every 50 feet, whereas for others, FWD measurements were taken at 0.5 mile intervals. Texas suffered a drought between 2006 and 2009 and very stiff subgrade values have been observed, especially for pavements over desiccated clay soils. Very stiff subgrade due to drought conditions may result in an un-conservative estimate of the pavement structural capacity, compared to the worst case conditions. Hence, it was ensured that a representative sample of pavement sections obtained, have FWD tests conducted prior to 2006.

FWD deflections (mils) along with the corresponding, actual applied loads (pounds) were recorded in the spreadsheet for each test station. In addition to the FWD data, the visual distress comments were also recorded based on the observations of the FWD crew during the data collection. Deflections were then normalized to a standard 9,000lb load which was used for subsequent calculations.

3.3.2 Back-calculation of Modulus

FWD deflection readings are obtained by applying a load to an 11.8” diameter load plate placed on the pavement during testing. These deflections are measured by seven sensors located at typical offsets of 12 inches from the load plate. The recorded pavement deflections in response to the applied load result in the FWD deflection basin. The FWD deflection basin is not unique and similar deflection basins can occur for different combinations of pavement structures.

The FWD data for each section was analyzed through the MODULUS back-calculation program. The MODULUS program output was stored in the spreadsheet, including, layer moduli for each layer and the subgrade. Though the SCI analysis uses M_R values determined by the AASHTO method, the back-calculated moduli can be used along with the supporting information for later comparisons with the SCI, to determine if the SCI provided a reasonable assessment of the pavement structural condition.

Figure 3.4 summarizes the distribution of pavement sections based on the average back-calculated subgrade modulus. Since the basic motive of this research is to validate the Structural Condition Index (SCI) method, this distribution shows that a very good sample of 180 pavement sections has been obtained, giving a balanced representation of Texas' subgrade conditions.

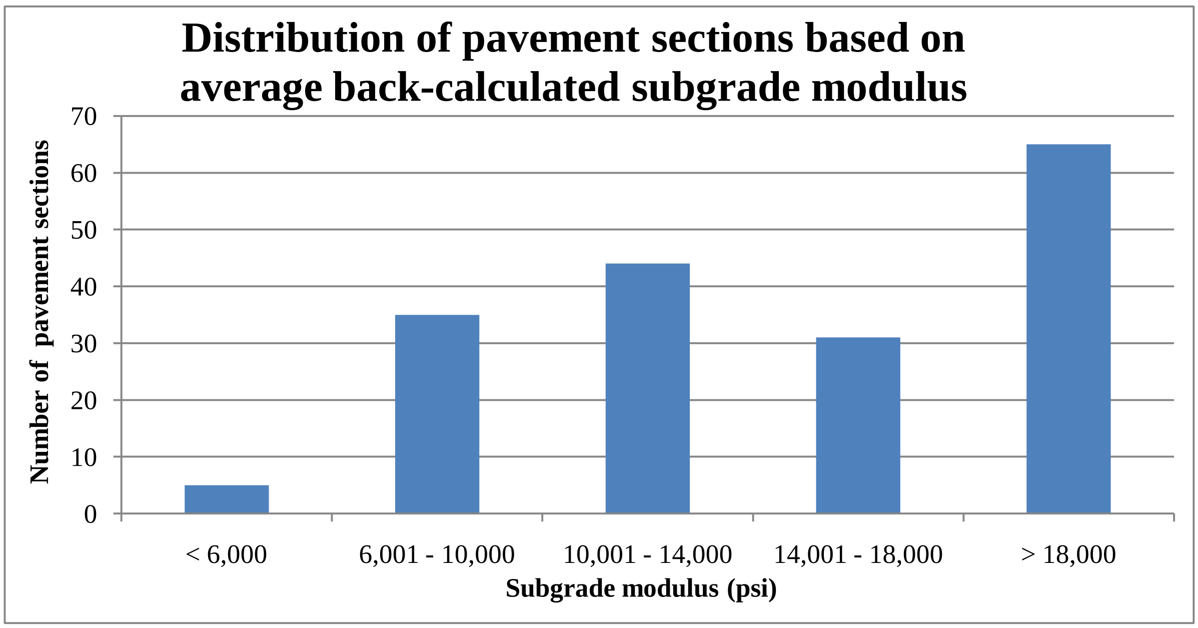


Figure 3.4 Distribution of pavement sections based on average back-calculated subgrade modulus

It should be noted that only a few pavement sections were observed with an average subgrade modulus at or below 6,000 psi. These very weak subgrades are primarily associated with pavements that are located in the wet climatic regions and have cracked unsealed surfaces and/or poor drainage conditions. Since the TxDOT maintenance forces are proactive in sealing pavements, and cleaning ditches & culverts, pavements in this condition are rare.

3.3.3 Pavement Thickness Information

The advantage of the Structural Condition Index (SCI) methodology is the use of total pavement thickness information instead of the layer thickness information. However, at present, only surface layer type and thickness range information can be obtained from the TxDOT PMIS. Hence, for this research, the pavement thickness information was usually obtained from the construction plan sheet, typical section details or pavement layer thickness and material type information from pavement forensic reports, and pavement designs or Load Zone Analysis requests. However, there were a few sections where the GPR, core log information or the DCP was conducted to obtain the pavement thickness information and such records of information sources were also stored in the spreadsheet. Table 3.5 summarizes the pavement layer and total thickness information for each of the route types in the 180 sections.

Table 3.5 Pavement layer and total thickness ranges for each route type

Route Type	Surface Type	Pavement Layer and Total Thickness			
FM	*Surface-Treated*	1”-5” Surface 5”-24” Flexible base Tot= 6”-26”	2”-6” Surface 5”-24” Treated base Tot= 7”-30”	1”-5” Surface 8”-19” Flexible base 6”-12” Treated subgrade Tot= 32”	1”-4” Surface 3”-8” Treated base 6”-15” Treated subgrade Tot= 15”-20”
FM	*Asphalt Concrete*	1.5”-13” Surface 5”-18” Flexible base Tot= 7”-23”	2”-6” Surface 7”-24” Treated base Tot= 9”-30”	7.5” Surface 14” Flexible base 6” Treated subgrade Tot=27.5”	1”-8” Surface 4”-9” Treated base 6”-12” Treated subgrade Tot= 14”-31.5”
SH	*Surface-Treated*	1”-2” Surface 5”-12” Flexible base Tot= 6”-13”	2” Surface 6” Treated base Tot= 8”	1” Surface 12” Treated base 8” Treated subgrade Tot= 21”	
SH	*Asphalt Concrete*	2”-6” Surface 4”-15” Flexible base Tot= 6”-21”	2”-3” Surface 6”-7” Treated base Tot= 8”-9”	2”-7” Surface 8”-10” Treated base 8”-15” Treated subgrade Tot= 18”-29.5”	

Table 3.5 (continued)

US & IH	*Asphalt Concrete*	1.5”-13” Surface 8”-18” Flexible base Tot= 11.5”-28”	2” Surface 10” Treated base Tot= 12”	3”-18.5” Surface 6”-12” Treated base 6”-12” Treated subgrade Tot= 26”-38”

3.3.4 Traffic Information

The traffic information was obtained from the TxDOT PMIS database. As discussed earlier, the traffic information is divided into five categories. The 30 million ESAL limit is selected for the “Very High” traffic category based on an administrative policy, which requires at least this traffic level for consideration of a perpetual pavement. Figure 3.5 shows the number of pavement sections in each traffic category. It should be noted that the available data, 180 sections, did not include “Very High” traffic category as there are only 10 in-service perpetual pavements in Texas [Lubinda 2010].

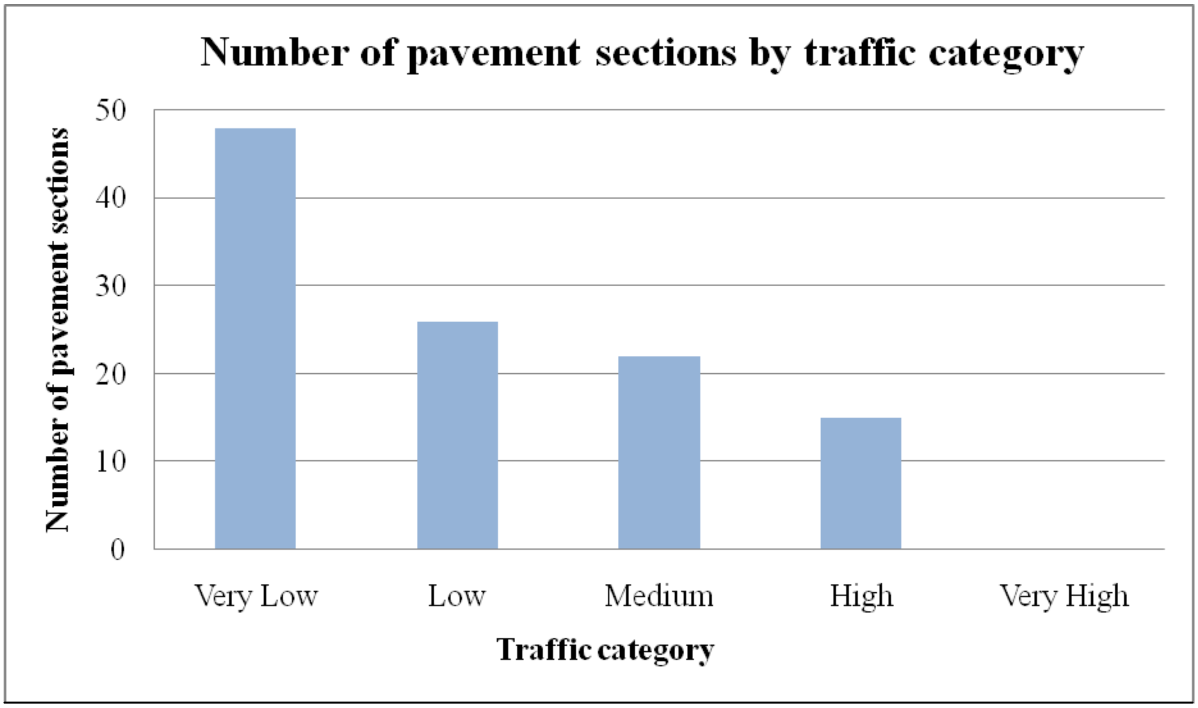


Figure 3.5 Number of pavement sections by traffic category

3.3.5 PMIS Scores

PMIS scores are not used in calculating the Structural Condition Index (SCI), but were used in the SCI threshold analysis (Chapter 6). PMIS scores located by Texas Reference Markers (TRM) for all 180 sections were obtained from the web-based Pavement Performance & Maintenance Management (PPMM) system as shown in Figure 3.6. This system is maintained by the Transportation Infrastructure and Information Systems Lab of the Center for Transportation Research at the University of Texas at Austin. The PPMM system is composed of two groups of modules, "Performance Monitoring" module and "Maintenance Management" module, each module having two corresponding tools [Tammy 2010]. Map-Zapper, a system that provides a user-friendly toolbox to use PMIS scores, was used to obtain TRM limits and offsets. Map-Zapper was also used for checking lane designations so as to ensure that the PMIS scores were from the same lane as the FWD data.

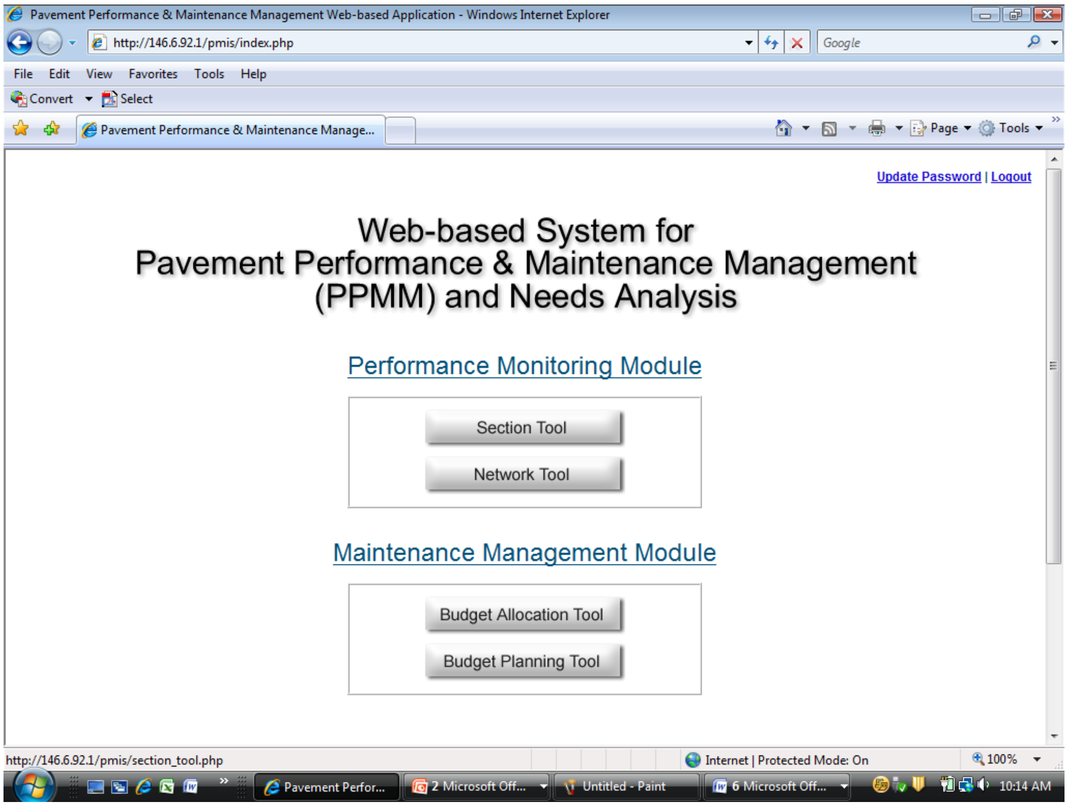
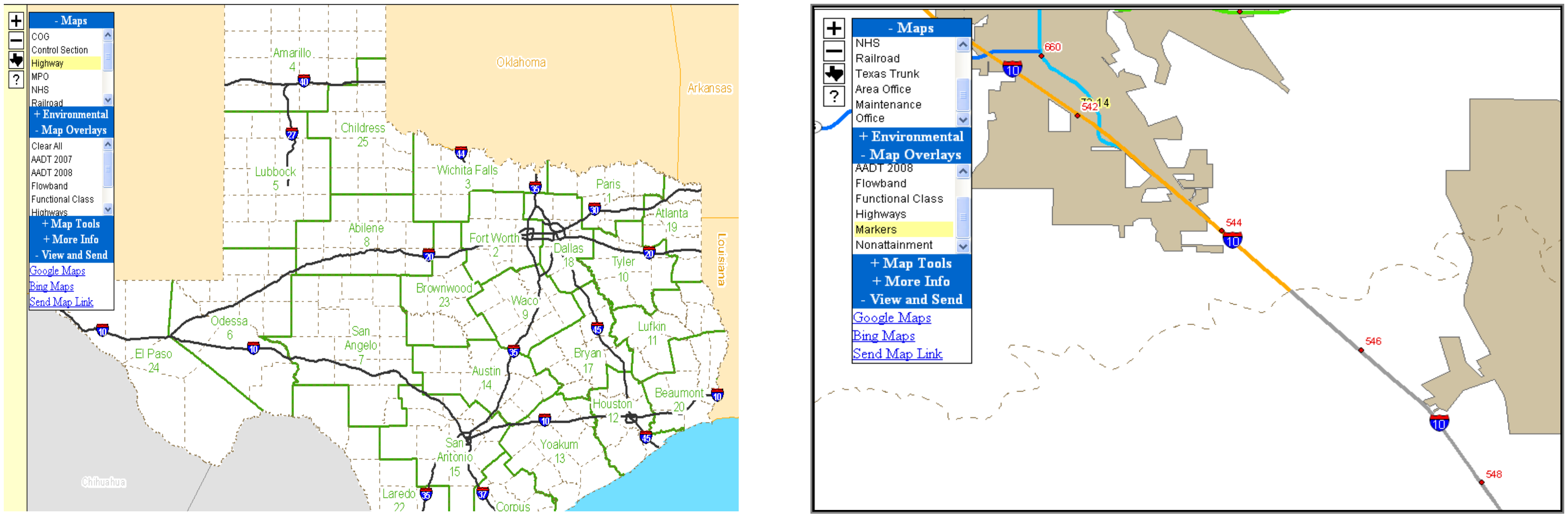


Figure 3.6 Pavement Performance & Maintenance Management (PPMM) menu screen

3.3.6 Aerial Maps and other Information sources

The Transportation Planning and Programming Division of TxDOT developed a web-based map similar to Google maps to display planning-related data. Users can pan & zoom, switch between multiple maps, overlay traffic counts, and, search & zoom to features [TxDOT 2008]. The TxDOT Statewide Planning Maps, as shown in Figure 3.7, were stored in the spreadsheet. Also, Google satellite aerial maps with the corresponding TRM's shown at the FWD test locations, as shown in Figure 3.8, were developed for each pavement section and stored in the spreadsheet.

Photos of the section or core data which depict the distressed areas were embedded in the spreadsheet when available, which helped to understand the pavement condition along a route. Based on the availability, the other types of data used for some of the sections were construction plan sheets, Form 1084 R 'Load Zoned Roadway Removal Request', Pavement design documents, Ground Penetrating Radar (GPR) data, Dynamic Cone Penetration (DCP) data, trench data and project-level pavement design traffic data from the Transportation Planning and Programming Division.



(a) Wide-angle view **(b) Close-up view**

Figure 3.7 TxDOT Statewide Planning Maps

[http://www.txdot.gov/apps/statewide_mapping/StatewidePlanningMap.html, Accessed November 2010]

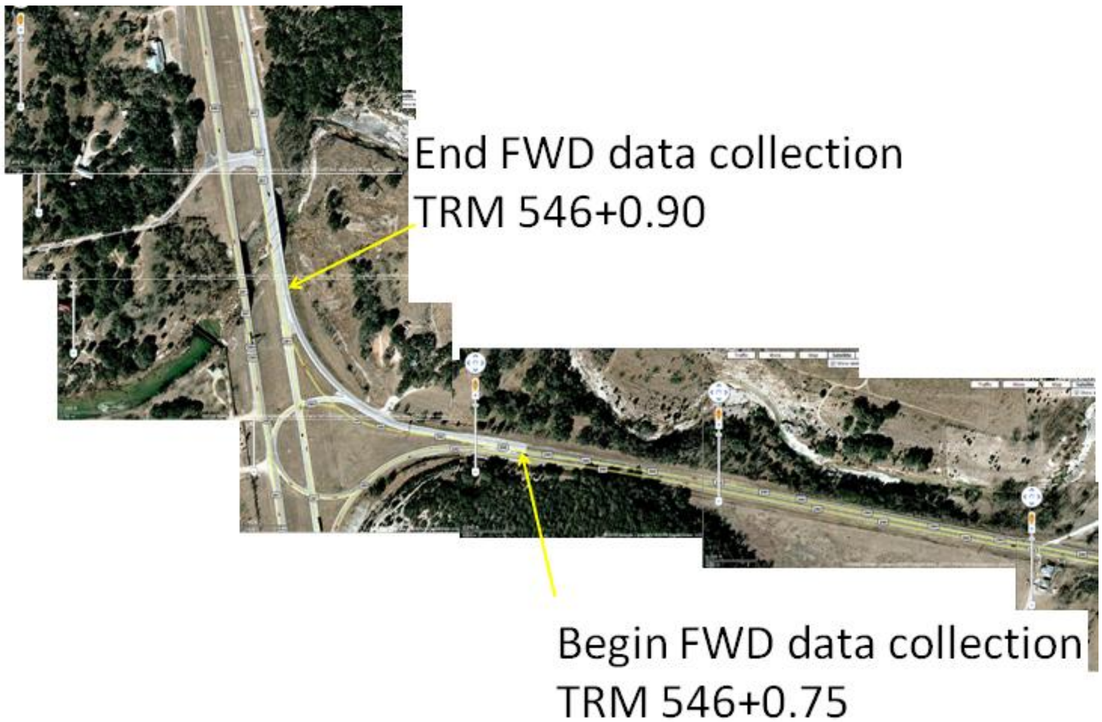


Figure 3.8 Google aerial online maps showing terrain and street system [Google 2010]

3.4 SUMMARY

This chapter presented the data related activities undertaken for this research. The process for data collection is discussed in this chapter. FWD data along with the supporting data for 180 pavement sections were collected from TxDOT, and summarized in a matrix chart. This chart summarizes the comprehensive sample of data, which is comprised of principle factors that could potentially affect the SCI values. The discussion of the SCI validation process, performed on the collected data, is presented in Chapter 4.

Chapter 4: Evaluation of the Structural Condition Index

4.1 DATA ANALYSIS

The Structural Condition Index (SCI) is a ratio of the ‘existing/effective’ AASHTO Structural Number (SN_{eff}) and the ‘required’ AASHTO Structural Number (SN_{req}). In order to assess the validation of the SCI, the Falling Weight Deflectometer (FWD) data along with the supporting data for 180 sections, as shown in Appendix B, was analyzed with an MS-Excel workbook, where the SCI for each of the sections was calculated following the procedures defined under Project 0-4322 [Zhang 2003]. The only change being, that a different SN_{req} lookup table, as shown in Table 4.1, was used in this research. This lookup table has more categories for the subgrade modulus and the estimated 20-year ESALs than the one in the previous research. The analysis results were summarized for each pavement section and graphically presented with plots of the SCI values over the length of the pavement section, along with the cumulative frequency distributions of the SCI values as illustrated in Figure 4.1.

SNreq for varying Traffic and Mr		20 -Year Accumultated Traffic in ESALs						
		Traffic Category		Very Low	Low	Moderate	High	Very High
		Range	Average	< 1,000,000	1,000,000 - 3,000,000	3,000,000 - 10,000,000	10,000,000 - 30,000,000	> 30,000,000
Mr (psi)	Subgrade Category			500,000	1,500,000	6,500,000	20,000,000	40,000,000
	Very Poor	< 6000	3000	4.4	4.9	5.9	6.9	7.5
	Poor	6,000 - 10,000	8000	3	3.5	4.4	5.1	5.6
	Fair	10,001 - 14,000	12000	2.5	3	3.8	4.5	5
	Good	14,001 - 18,000	16000	2.3	2.7	3.4	4	4.5
	Very Good	> 18,000	24000	2	2.3	3	3.5	4

Table 4.1 SN_{req} look up table used in the SCI analysis

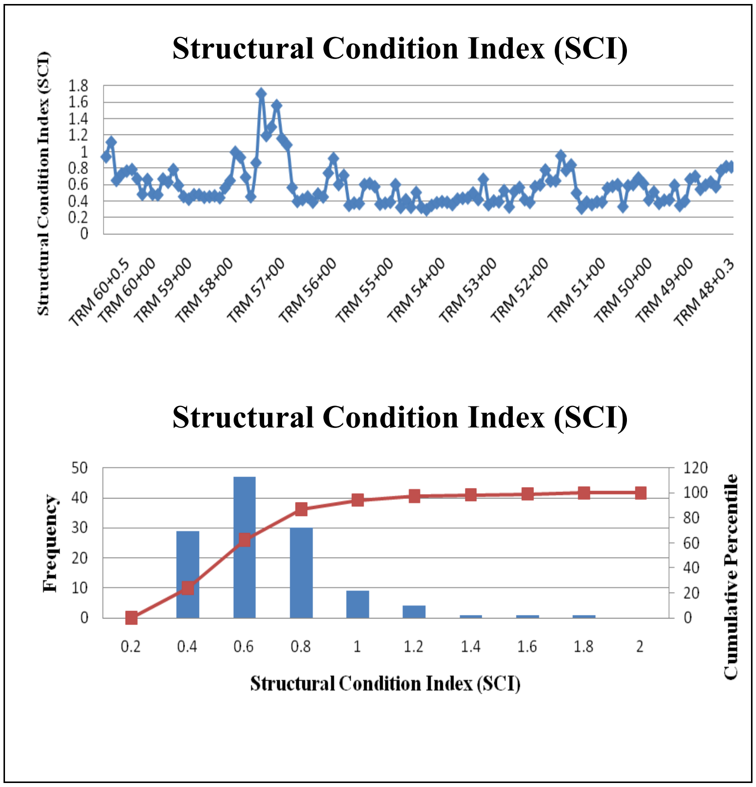


Figure 4.1 Graphical summary of the SCI results for a pavement section

To facilitate the implementation of the SCI methodology by TxDOT, an SCI algorithm tool was also developed in a macro-enabled excel workbook using Visual Basic Applications (VBA) as shown in Appendix C. The tool acts as an interface between the SCI methodology and the users. The user can input the required data, run the SCI algorithm and view the SCI analysis results. A user manual was also developed to aid the user in the understanding of the SCI algorithm and is attached in Appendix D.

4.2 VALIDATION OF THE STRUCTURAL CONDITION INDEX (SCI)

One of the primary objectives of this research is to validate the SCI method. As part of the validation process, the calculated SCI values were compared with those values obtained from the mechanistic analysis of the same pavement section. More detailed discussions of the mechanistic analysis are presented in this section.

The mechanistic analysis was conducted using WESLEA, a linear elastic layered theory program [Van Cauwelaert 1989]. The pavement mechanistic responses such as the stress, strain and deflection were determined using the WESLEA program. Seven pavement sections, with 380 data points, were used in the analysis as listed in Table 4.2.

Table 4.2 Data used in the SCI Validation Process

Route	Environmental Zone	Subgrade Soil Category	Estimated 20-year ESALs	Total Pavement Thickness (inches)
US 259 NB	Wet-Cold	Very Good	3,500,000	15.5
US 259 SB	Wet-Cold	Very Good	2,438,000	16.1
FM 486	Mixed	Poor	1,082,000	7
FM 2199	Wet-Cold	Poor	1,404,000	9
US 69 NB	Wet-Warm	Poor	10,719,000	17.5
SL 375 L2	Dry-Warm	Poor	2,798,000	13
SH 195	Mixed	Fair	10,385,000	16

4.2.1 Asphalt Institute (AI) Rutting and Fatigue Models

The vertical compressive strain at the top of the subgrade and the horizontal tensile strain at the bottom of the surface layer were determined at each FWD test point for the seven sections, using the WESLEA program. Based on the estimated strain values from the Asphalt Institute (AI) rutting and fatigue equations [TAI 1982], ESALs to failure was computed. It should be noted that, ESALS to failure can also be computed from other models such as the Shell rutting and fatigue models. Since TxDOT currently uses the AI rutting and fatigue models to conduct mechanistic checks of the FPS-19W flexible pavement design solutions, the AI rutting and fatigue models were used in this research, which are presented as follows:

$$N_d = 1.365 * 10^{-9}.(\varepsilon_c)^{-4.477} \tag{4.1}$$

Where:

N_d = Number of ESALs to rutting failure

ε_c = Vertical compressive strain at the top of the subgrade

$$N_f = 0.0796 * 10^{-9}.(\varepsilon_t)^{-3.291}.(E)^{-0.854} \tag{4.2}$$

Where:

N_f = Number of ESALs to fatigue failure

ε_t = Horizontal tensile strain at the bottom of asphalt concrete (AC) layer

E = Surface layer modulus

4.2.2 Rutting ratio and Fatigue ratio

Factors that represent the percentage of remaining life, analogous to the SCI, have been derived by calculating the ratio of ESALs to failure (from the AI rutting and fatigue models), and the estimated 20-year ESALs. These factors were referred to as the rutting ratio and the fatigue ratio respectively in the analysis as shown in Equations 4.3 and 4.4.

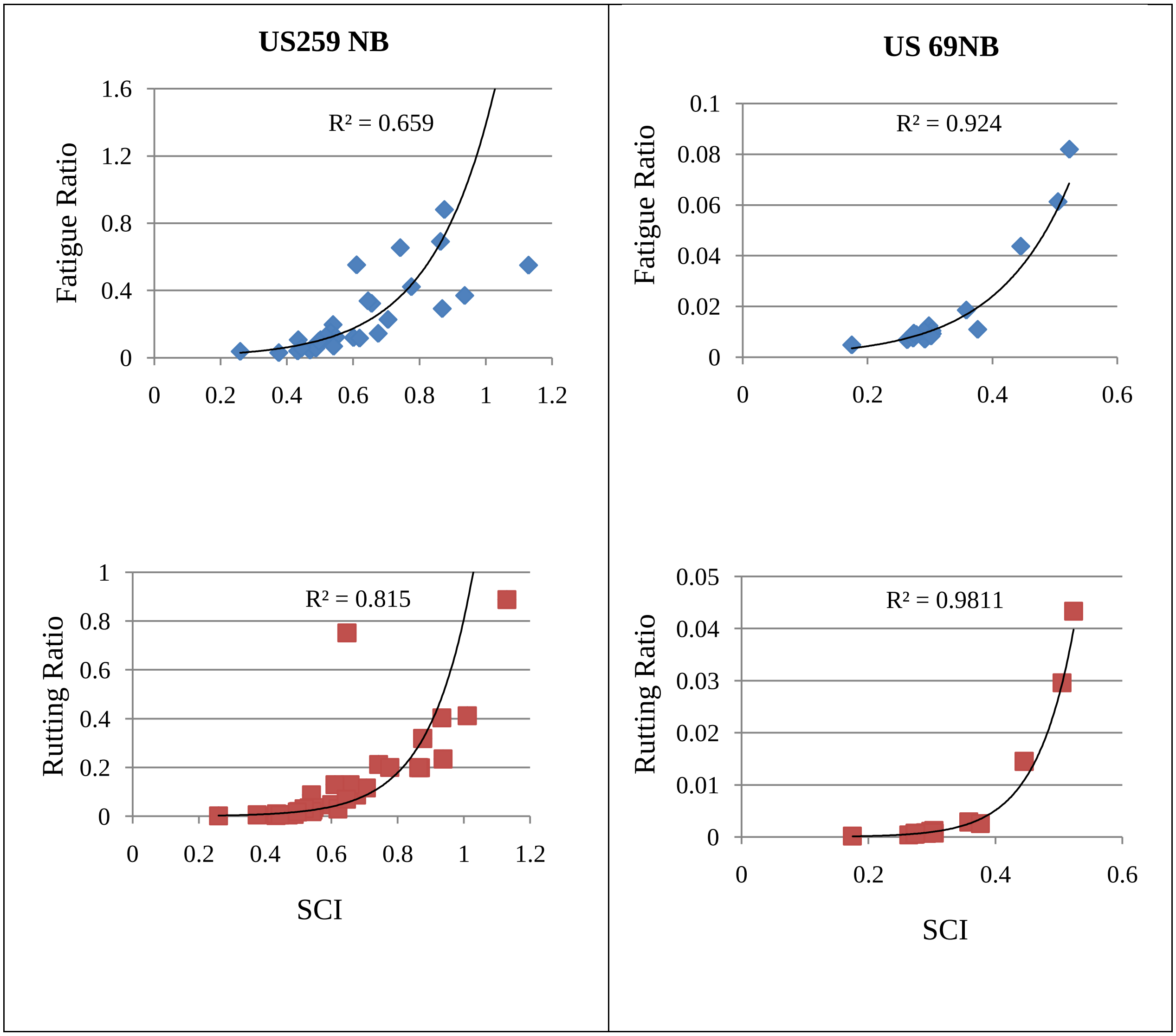
$$Rutting\ Ratio = \frac{Number\ of\ ESALS\ to\ rutting\ failure}{Estimated\ 20 - year\ ESALs} \tag{4.3}$$

$$Fatigue\ Ratio = \frac{Number\ of\ ESALS\ to\ fatigue\ failure}{Estimated\ 20 - year\ ESALs} \tag{4.4}$$

4.2.3 Validation Analysis Results

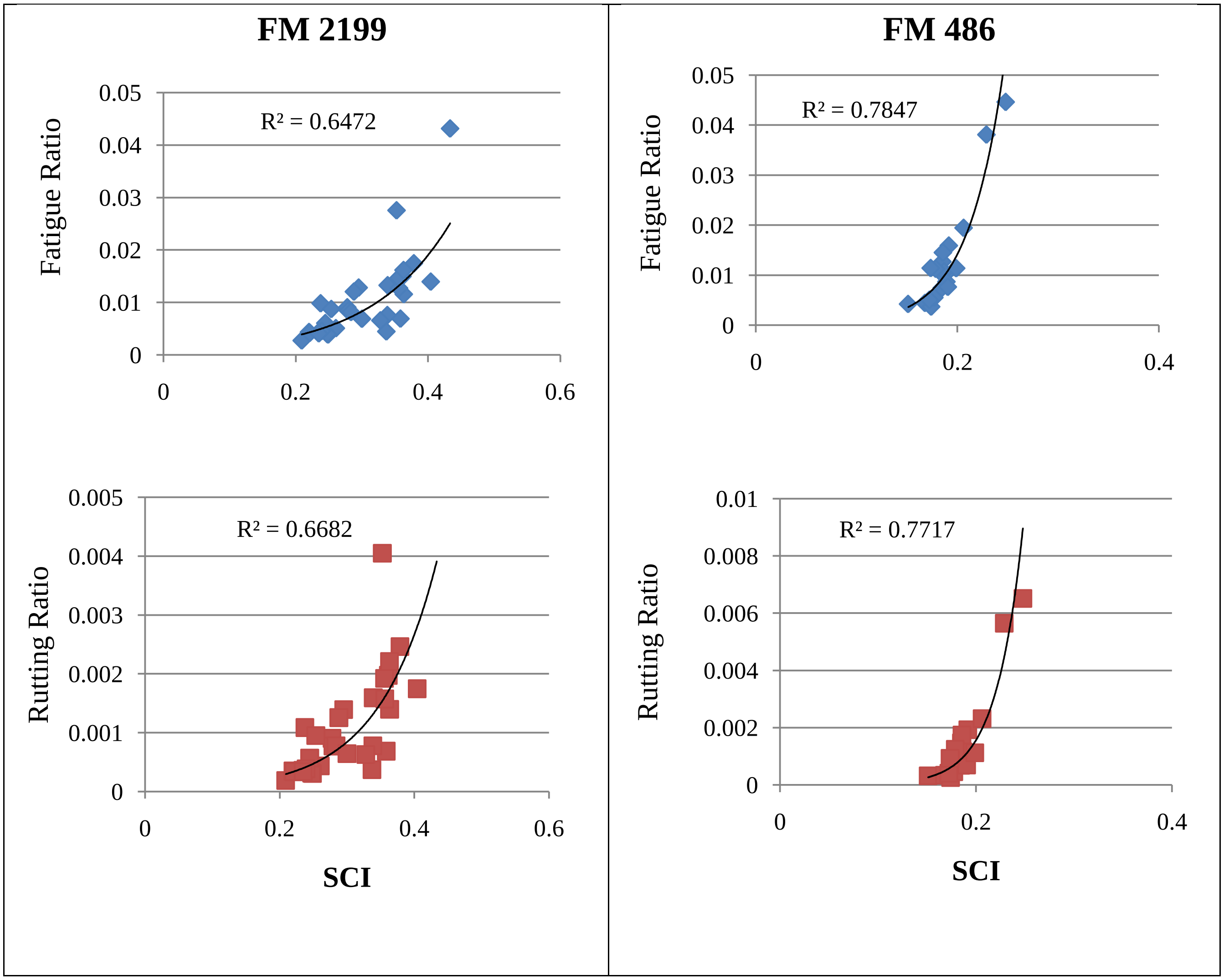
The SCI validation was conducted using the seven pavement sections listed in Table 4.2. However, for the discussions in this section, the focus is on four particular cases which broadly represent the pavement types that were expected to affect the SCI values. The four pavement types considered in the discussion are as follows: (a) Thick asphalt concrete surface - US 69NB, (b) Thin asphalt concrete surface - FM 486, (c) Thick surface-treated - US 259NB, and (d) Thin surface-treated - FM 2199. For the purposes of this validation, a pavement structure having a total pavement thickness greater than 10 inches was considered as "thick", and the one having a total pavement thickness less than 10 inches was considered as "thin".

A non-linear regression was performed for each of the cases to determine the correlation between the rutting/ fatigue ratio and the SCI values. The rutting/fatigue ratios were computed for each of the FWD test points and then compared to the SCI value for the same point. The coefficient of determination (R^2) was used for comparison. The regression graphs for the thick and the thin pavement structures were plotted separately as shown in Figure 4.2 and Figure 4.3. The initial observations made from the regression graphs were that that the SCI values are more correlated to the rutting and fatigue ratios for the thick pavement structures than for the thin pavement structures. The values of R^2 for the thick pavement structures were in the range of 0.8-0.9 whereas the R^2 values for the thin pavement structures were in the range of 0.6-0.7. Since the validity of the SCI methodology cannot be simply judged from the R^2 values, hypothesis testing was conducted for the four pavement types to further support the validation process.



(a) Surface-treated **(b) Asphalt Concrete**

Figure 4.2 Correlation between the fatigue/rutting ratios and the SCI values for a thick pavement structure



(a) Surface-treated **(b) Asphalt Concrete**

Figure 4.3 Correlation between the fatigue/rutting ratios and the SCI values for a thin pavement structure

For purposes of determining the statistical significance of the coefficient of determination (R^2), the Student's t-test has been conducted for each of the four pavement types with Equation 4.5. The null hypothesis used in the analysis was that, there is no correlation between the SCI values and the fatigue/rutting ratios. The results from the t-test showed that this null hypothesis was rejected with a 99% confidence level using a two-tailed Student's t-distribution in all cases as shown in Table 4.3. Therefore, it was concluded that the SCI values and the fatigue/rutting ratios are correlated, thereby validating the SCI methodology.

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}} \tag{4.5}$$

Where:

t	=	t-test statistic
R^2	=	coefficient of determination
n	=	sample size

Table 4.3 Hypothesis Testing Results for the Four Pavement Types

Section	Pavement Type	R^2		Sample Size (n)	Null Hypothesis Result
		SCI vs. Fatigue ratio	SCI vs. Rutting ratio		
US 259 NB	Thick surface-treated	0.659	0.815	34	Reject
US 69NB	Thick AC	0.924	0.9811	33	Reject
FM 2199	Thin surface-treated	0.6472	0.6682	20	Reject
FM 486	Thin AC	0.7847	0.7717	19	Reject

The validation procedure till this point looked at the four pavement types separately: thick surface-treated, thick asphalt concrete, thin surface-treated and thin asphalt concrete. To verify if the SCI validation results hold even when all the four pavement types are grouped together as one, another regression was carried between the fatigue/rutting ratios and the SCI values. The coefficient of determination (R^2) was computed for the four pavement types grouped together and are shown in Figure 4.4. The results indicated that a high correlation exists between the SCI values and the fatigue/rutting ratios. Based on the relationship between the structural condition from the mechanistic analysis method and the SCI values for the entire group of pavements, the SCI can be further stated as a reliable index.

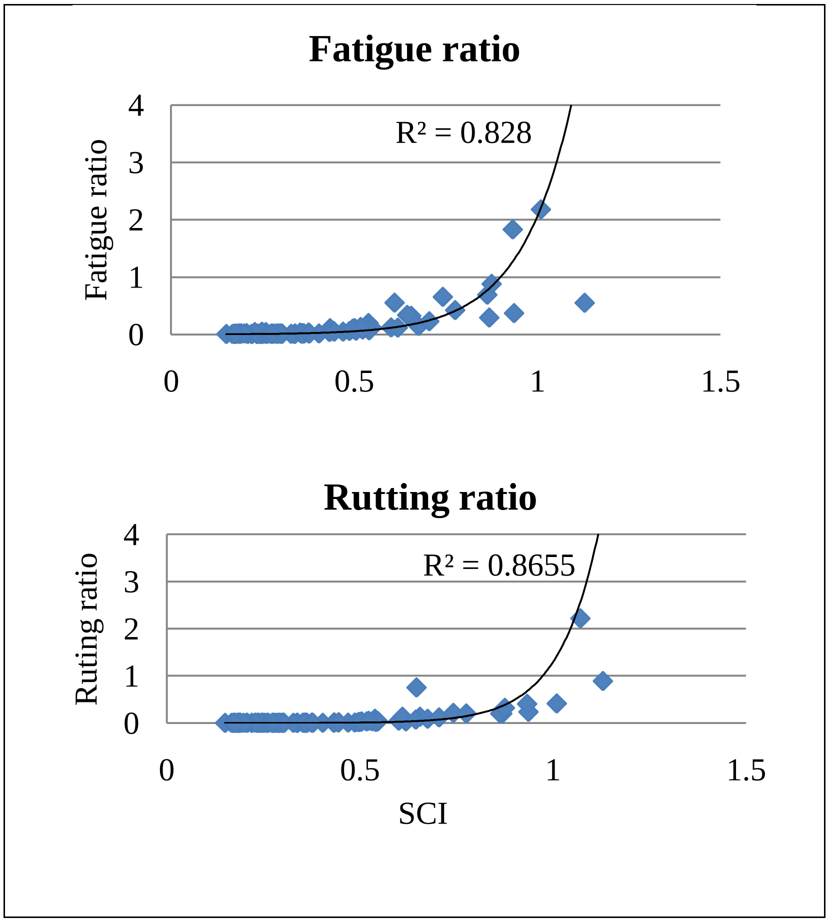
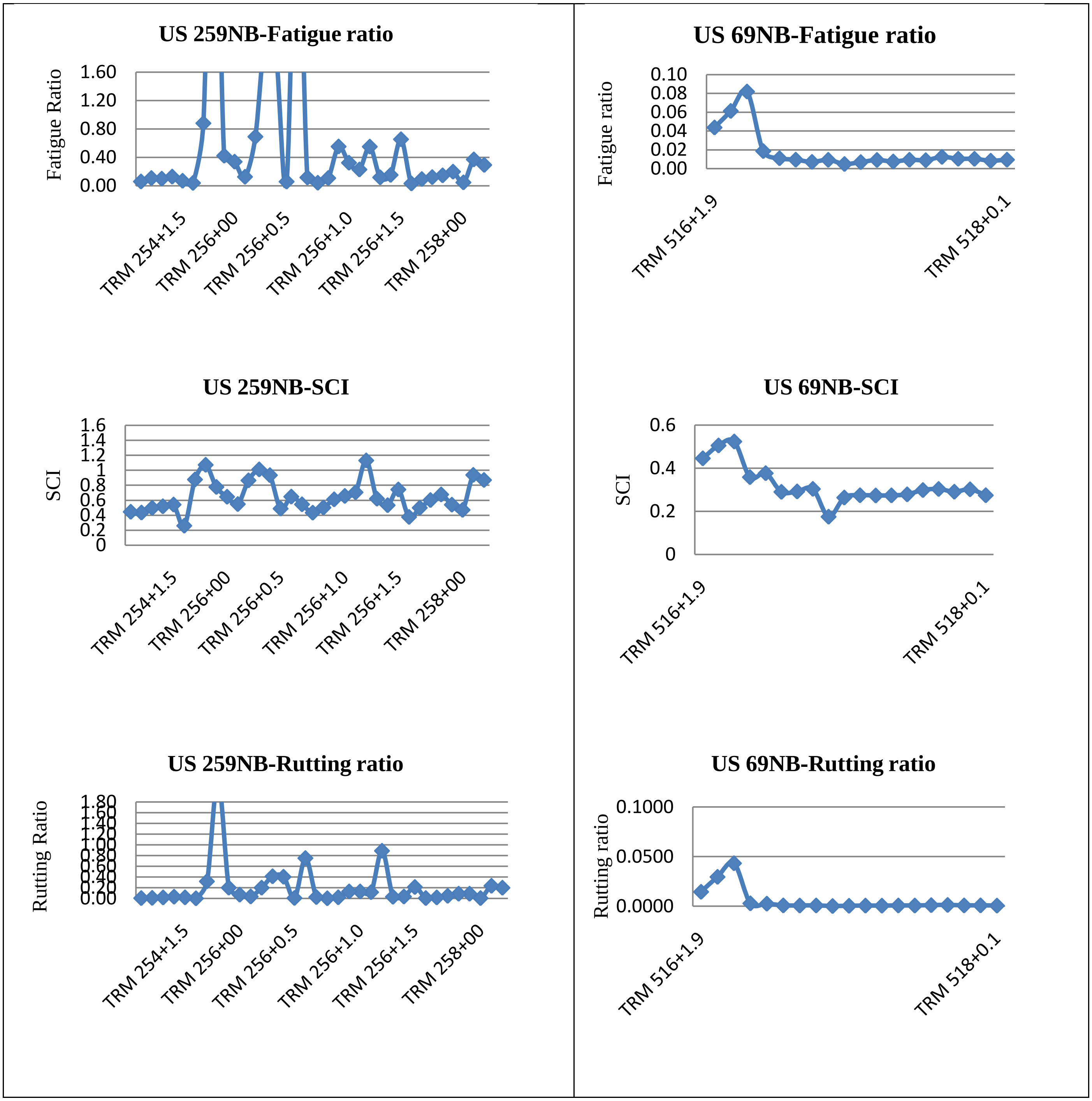


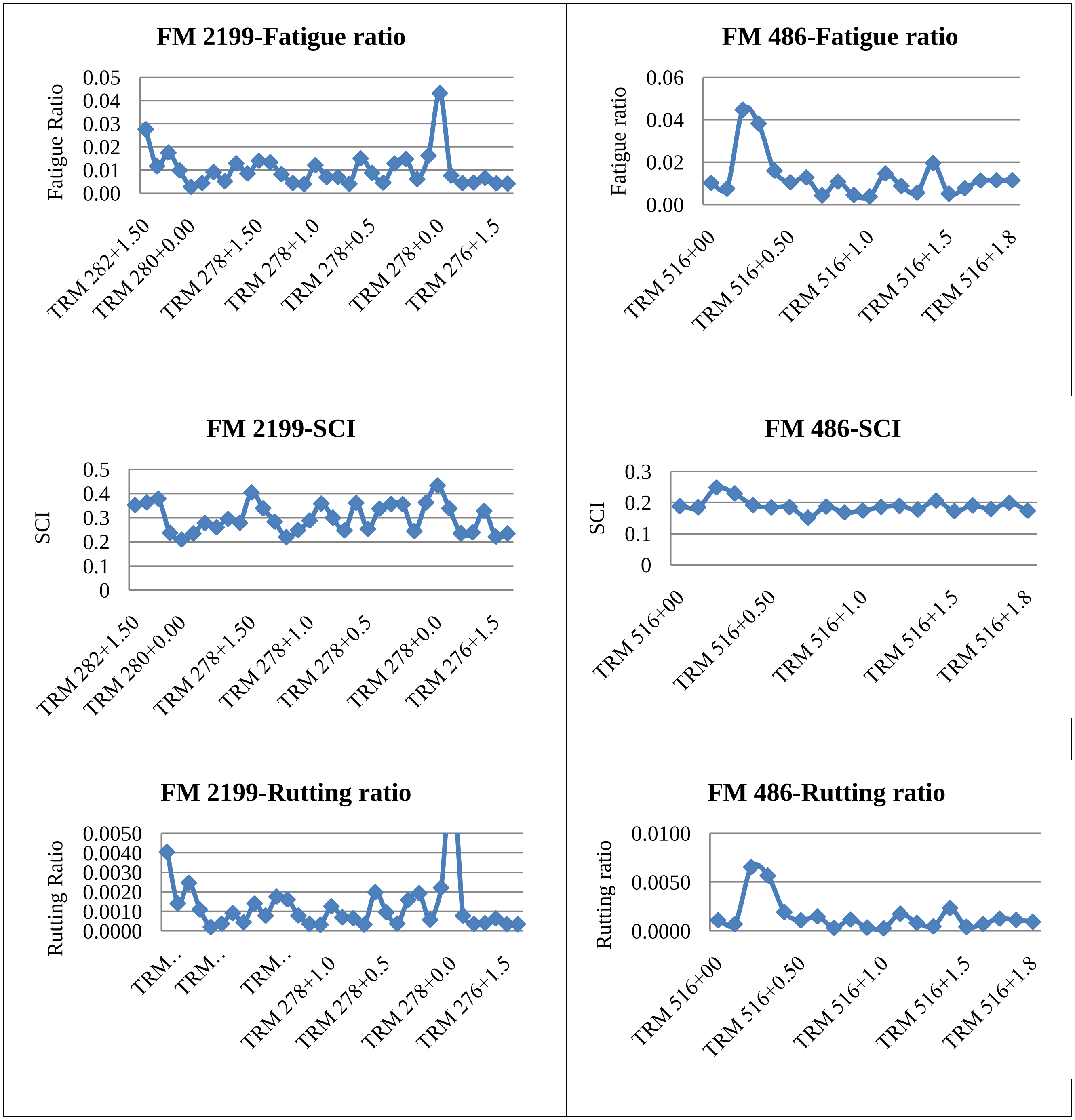
Figure 4.4 Correlation between the SCI values and the fatigue/rutting ratios for the grouped pavements

The trends for the SCI values, the fatigue ratio, and the rutting ratio observed for the thick and the thin pavement structures are plotted in Figure 4.5 and Figure 4.6 respectively. It was found that the trend of the SCI values is the same as the trends for fatigue ratio and rutting ratio, along the same pavement section. Also, the peaks in the SCI graph correspond to the peaks in the mechanistic graphs. Generally, a change in the thickness of a pavement structure or a patch at the FWD test point results in unusual performance in comparison to the neighboring data of a pavement section. As an example, it was found that the total pavement thickness varies along the US 259NB section, which resulted in the peak points as seen in Figure 4.5a. Similar observations were made about the pavement structural condition using both the SCI method and the mechanistic method. These observations are further a positive confirmation about the rational results obtained from the SCI methodology.



(a) Surface-treated **(b) Asphalt Concrete**

Figure 4.5 Comparison of trends between the fatigue/rutting ratios and the SCI values for a thick pavement structure



(a) Surface-treated **(b) Asphalt Concrete**

Figure 4.6 Comparison of trends between the fatigue/rutting ratios and the SCI values for a thin pavement structure

4.3 SENSITIVITY OF SCI TO TOTAL PAVEMENT THICKNESS

The total pavement thickness information is used as an input in the SCI method and is obtained from multiple sources such as the GPR or coring. However, it is very probable that the pavement thickness estimates are not accurate because of factors such as construction practices among others. Hence, an analysis was undertaken to estimate the expected error in the SCI values due to error in the total pavement thickness estimates.

The SCI is a ratio of the effective SN (SN_{eff}) to the required SN; and the SN_{eff} is dependent on the total pavement thickness information. Using these relationships, the change in the SCI estimate due to the change in the total pavement thickness was determined using the sensitivity analysis using Equations 4.6a to 4.6e. SN_{eff} is also dependent on the pavement surface type: surface-treated or asphalt concrete. Thus, the SCI error estimates will vary according to the pavement surface type. Based on the Equation 4.6e, a generalized trend showing the sensitivity of the SCI error estimates for different pavement surface type is plotted in Figure 4.7.

$$SCI = \frac{SN_{eff}}{SN_{req}} \tag{4.6a}$$

$$SN_{eff} = f(H_p) = k_1 \times SIP^{k_2} \times H_p^{k_3} \tag{4.6b}$$

Where:

k_1, k_2, and k_3	=	Regression coefficients [Rohde 1994]
SIP	=	Structural index of pavement [Rohde 1994]

H_p = Total pavement thickness

$$SCI = c \times H_p^{k_3} \tag{4.6c}$$

Where:

$$c = \frac{k_1 \times SIP^{k_2}}{SN_{req}}$$

$$\ln(SCI) = \ln(c) + k_3 \times \ln(H_p) \tag{4.6d}$$

$$\frac{\Delta SCI}{SCI} = k_3 \times \frac{\Delta H_p}{H_p} \tag{4.6e}$$

Where:

k_3 = 0.7581 and 0.8241 for surface-treated and asphalt concrete pavement surface respectively

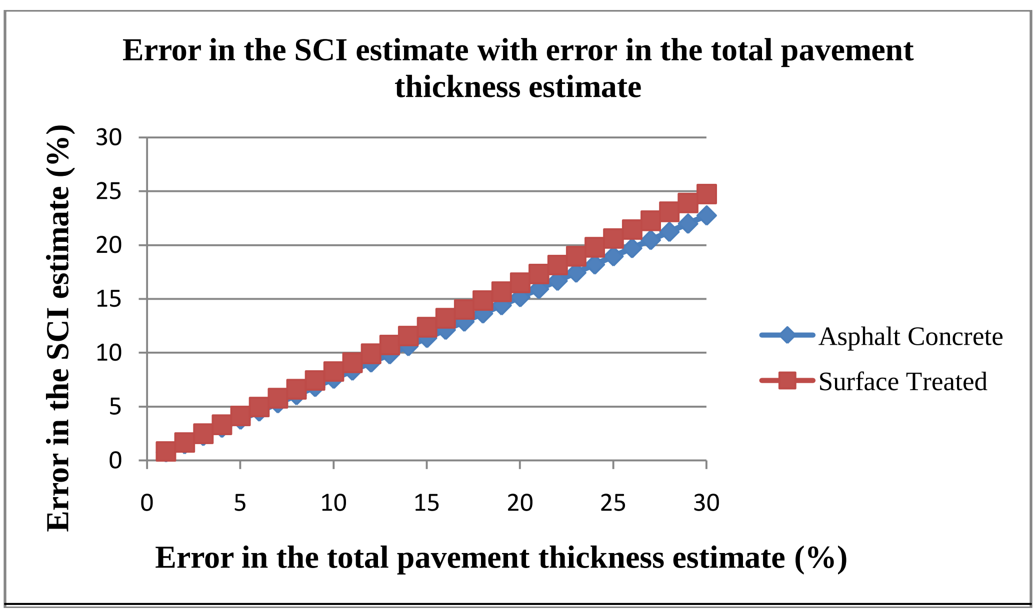


Figure 4.7 Sensitivity of the SCI estimate to the Total Pavement Thickness estimate

To quantify the error for the SCI estimate using Figure 4.7, field data on the expected pavement thickness error is required. Certain assumptions on the total pavement thickness variability were made using an engineering judgment. Table 4.4 summarizes the assumed variability in the total pavement thickness and the corresponding expected error in the SCI estimates. The results indicated that there is a significant impact on the SCI estimate with variability in the total pavement thickness estimate.

Table 4.4 Sensitivity of the SCI estimate to the Total Pavement Thickness estimate

Pavement type	Assumed total pavement thickness variability (%)	Expected error in the SCI estimate (%)	
		Surface-treated	Asphalt Concrete
Newly constructed pavements with total thickness <8”	12.5	9.09	9.88
Newly constructed pavements with total thickness > 20”	10	7.58	8.24
Old pavement structures	10-30	7.58-22.7	7.58-24.7
Surface-treated	10-15	7.58-11.37	7.58-12.36
ACP	10-15	7.58-12.36	7.58-12.36

4.4 EFFECT OF SHALLOW BEDROCK ON STRUCTURAL CONDITION INDEX

The Structural Condition Index (SCI) calculations are dependent on the FWD deflection data. Large FWD deflections at the seventh sensor (W_7) location (72” from the load plate) are usually related to a weaker subgrade. However, based on experience with Texas' conditions, low W_7 values may either be due to a strong subgrade or a weak subgrade over relatively shallow bedrock. Hence, this analysis was undertaken to determine if the calculated SCI values for a pavement structure with shallow bedrock provide a different interpretation of the same pavement structure with deep bedrock.

The subgrade modulus, the total pavement thickness and the bedrock depth are the three important factors used for the analysis. Based on the literature review and discussions with the PD, these factors were broadly categorized as shown in Table 4.5.

Table 4.5 Factors considered in the Bedrock Depth analysis

Subgrade Modulus (ksi)	**Total Pavement Thickness (inches)**	**Bedrock Depth (inches)**
Weak (<8 ksi)	Thin (<10")	Shallow (<60")
Strong (>14 ksi)	Intermediate (10"-16")	Intermediate (60"-180")
	Thick (>16")	Deep (>180")

4.4.1 Data source

The analysis was initially planned to be conducted with bedrock depth measurement (e.g. using auger or Dynamic Cone Penetrometer measurements) data collected on in-service pavement sections. However, due to the lack of pavement sections with actual bedrock depth measurements, the analysis was done using a comprehensive set of FWD deflection data calculated with the BISAR program [de Jong 1973]. BISAR is a linear elastic layered theory program which computes mechanistic responses such as deflections, stresses and strains within a pavement structure. This program was used to analyze over 7 million hypothetical pavement structures in a previous research [Murphy 1998]. These pavement structures were modeled based on the survey information from the TxDOT District and Division personnel about the layer thicknesses and the material types used in Texas. The resulting data was stored in a SYBASE SQL database which was called ‘NETFWD’ [Murphy 1998].

An example of the NETFWD database output is shown in Figure 4.8 which lists the pavement layer thicknesses, the moduli values, depth to rigid layer, and the FWD deflections for over 400,000 pavement structures with a surface modulus of 450 ksi. As it can be seen, in the Figure 4.8, all other factors held constant, the FWD deflections increase as the depth to rigid layer decreases. Since the SCI index is directly related to the FWD deflections, it is important to determine if these changes in FWD deflections due to changes in the bedrock depth would change the conclusions about the pavement structural condition.

K31 fx 7.99

	B	C	D	E	F	G	H	I	J	K	L
1	Surf Thickness	Base Modulus	Base Thickness	Subgrade Modulus	Subgrade Thickness	Total Pavt Thk	w1	w2	w3	w4	w5
2	2.5	15	6	4	30	8.5	53.7	28.2	10.3	3.21	0.61
3	2.5	15	6	4	40	8.5	57.1	31.4	12.9	5.01	1.69
4	2.5	15	6	4	50	8.5	59.5	33.7	14.9	6.53	2.75
5	2.5	15	6	4	60	8.5	61.2	35.4	16.4	7.78	3.72
6	2.5	15	6	4	70	8.5	62.6	36.6	17.5	8.81	4.56
7	2.5	15	6	4	80	8.5	63.6	37.7	18.5	9.66	5.29
8	2.5	15	6	4	90	8.5	64.4	38.5	19.3	10.4	5.91
9	2.5	15	6	4	100	8.5	65.1	39.2	19.9	11	6.46
10	2.5	15	6	4	110	8.5	65.7	39.7	20.5	11.5	6.93
11	2.5	15	6	4	120	8.5	66.2	40.2	20.9	11.9	7.34
12	2.5	15	6	4	130	8.5	66.6	40.6	21.3	12.3	7.7
13	2.5	15	6	4	140	8.5	67	41	21.7	12.7	8.02
14	2.5	15	6	4	150	8.5	67.3	41.3	22	13	8.31
15	2.5	15	6	4	180	8.5	68.1	42.1	22.8	13.7	9

Figure 4.8 NETFWD database

4.4.2 Experiment

In order to make the analysis practical, a total of 104 pavement sections were selected from the initial 400,000 pavement sections obtained from the NETFWD database. These 104 pavement sections included a range of bedrock depths from 40" to 720". The existing/effective Structural Number (SN_{eff}) was calculated using the AASHTO material stiffness coefficient and thickness equation as shown in Equation 4.7. Table 4.6 shows the assumptions about the material stiffness coefficients for asphalt concrete pavement (ACP) surface and base, which were made using the AASHTO guide for the design of Pavement Structures [AASHTO 1986].

$$SN = a_1 d_1 + \sum_{i=1}^{n} a_i d_i m_i \tag{4.7}$$

Where:

SN	=	Structural Number
a_i	=	Structural layer coefficients
d_i	=	Layer thickness
m_i	=	Moisture coefficients

Table 4.6 AASHTO Material Stiffness coefficients

Material type	Modulus(ksi)	AASHTO coefficient
ACP	450	0.44
Flexible base	<90	0.14
Lime-stabilized base	120-240	0.20
Cement-stabilized base	500-1,000	0.30

4.4.3 Assumptions about the Traffic information

The required AASHTO Structural Number (SN_{req}) is calculated from the subgrade modulus (M_R) and the traffic information [AASHTO 1993]. The TxDOT PMIS database has traffic information for in-service pavements. However, since this analysis was based on modeled pavement structures from the NETFWD, the traffic information cannot be obtained from the TxDOT PMIS. Hence, based on an engineering judgment, the traffic assumptions were made using the available thickness information as shown in Table 4.7.

Table 4.7 Assumptions of traffic information based on the total pavement thickness

Total Pavement Thickness (inches)	Traffic Category	Range of Traffic (20-year ESALs)
Thin pavements (<10”)	Low traffic	1,000,000 - 3,000,000
Intermediate pavements (10" - 16")	Medium traffic	3,000,000 - 10,000,000
Thick pavements (>16")	High traffic	10,000,000 - 30,000,000

The SCI values were thus computed as a ratio of SN_{eff} and SN_{req}. The SN_{eff} was calculated from the AASHTO's material stiffness and thickness equation and, the SN_{req} calculated using the subgrade modulus (determined by the AASHTO method), and the assumed traffic which was linked to the total pavement thickness.

4.4.4 Observations made from the analysis

The following observations were made from the analysis:

- It was observed that the SCI values tend to decrease as the bedrock depth increases with other factors, such as the subgrade modulus and the total pavement thickness, held constant, as shown in Figure 4.9. Also, the SCI values tend to stabilize at relatively lower bedrock depths for a pavement structure on a weak subgrade than for the same pavement structure on strong subgrade.

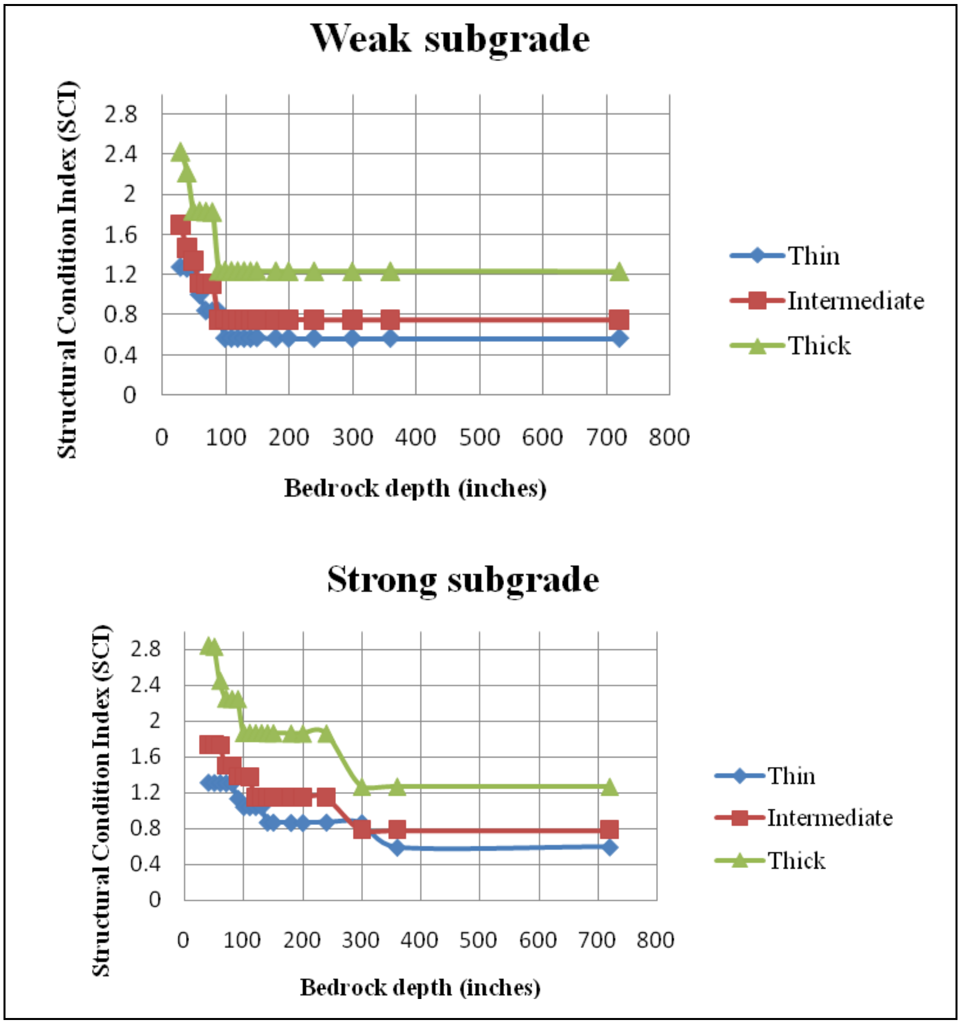


Figure 4.9 Effect of the bedrock depth on the SCI values

- *Thin/intermediate pavement structures on a weak/strong subgrade:* The effect of the bedrock depth on the SCI values was found to have a significant impact on intermediate and thin pavement structures which are either over a weak/strong subgrade. From Figure 4.9, it can be observed that the SCI values are greater than 1 at shallow bedrock depths for both types of subgrade, indicating that the thin and the intermediate pavement structures are structurally adequate at shallow bedrock depths. However, the interpretation changes as the bedrock depth increases beyond 100”. In this scenario, the SCI values for the thin and the intermediate pavement structures are below the threshold value of 1, indicating that the pavement structures are structurally inadequate. Thus, the structural interpretations of the same thin/intermediate pavement structures on both types of subgrade over shallow and deep bedrock depths are very different.

- *Thick pavement structures on a weak/strong subgrade*: On the other hand, the thick pavement structure is structurally sound at both shallow and deep bedrock depths on either a weak or a strong subgrade. At shallow bedrock depths, the SCI values for a thick pavement structure are around 2 which indicate that the pavement structure is substantially over-designed from an engineering point of view. However, at larger bedrock depths, the same thick pavement structure is structurally sound and only slightly over-designed.
- The sensitivity of the SCI to the bedrock depth with varying subgrade modulus and total pavement thickness is summarized in Table 4.8, where ‘Yes’ is stated when there is a change in the SCI value with bedrock depth, else ‘No’ is stated.

Table 4.8 Effect of the Bedrock Depth on the SCI values

Thin Pavements (<10")										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Intermediate Pavements (10"-16")										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Thick Pavements (>16")										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

4.5 CONCLUSIONS

This chapter discussed the SCI validation process carried out using the mechanistic analysis. The percent-remaining-life factors, called the fatigue ratio and the rutting ratio, were derived using the Asphalt Institute (AI) fatigue and rutting equations respectively. A non-linear regression analysis, conducted with these ratios and the SCI values on the four pavement types: thick asphalt concrete, thick surface-treated, thin asphalt concrete, and thin surface-treated; and the grouped pavements (four pavement types together), show that a correlation exists, indicating that the SCI method provides rational results. The results for hypothesis testing on the statistical significance of the correlation further validate the SCI method.

Since the total pavement thickness changes with factors such as the age of the pavement, construction practices etc; a significant error can be associated with the total pavement thickness estimates. The total pavement thickness is used as an input in the SCI methodology and hence, the expected error in the SCI estimate was found out using the sensitivity analysis.

An analysis to determine the effect of the shallow bedrock depth on the SCI analysis was also undertaken using the NETFWD-modeled pavement structures. The results show that the SCI values tend to decrease as the bedrock depth increases with other factors, such as the subgrade modulus and the total pavement thickness, held constant. The results indicate that the thin and intermediate pavement structures on a weak/strong subgrade over shallow bedrock depths are structurally sound; however, the same pavement structures are found to be structurally inadequate at higher bedrock depths. At shallow bedrock depths, the thick pavement structure is identified as an over-designed pavement structure from an engineering point of view. However, at larger bedrock depths, the same thick pavement structure is structurally sound and slightly over-designed. These results thus conclude that the shallow bedrock depth plays a significant role in affecting the SCI values.

Chapter 5: Characterizing the Representative SCI Value of a Section

5.1 INTRODUCTION

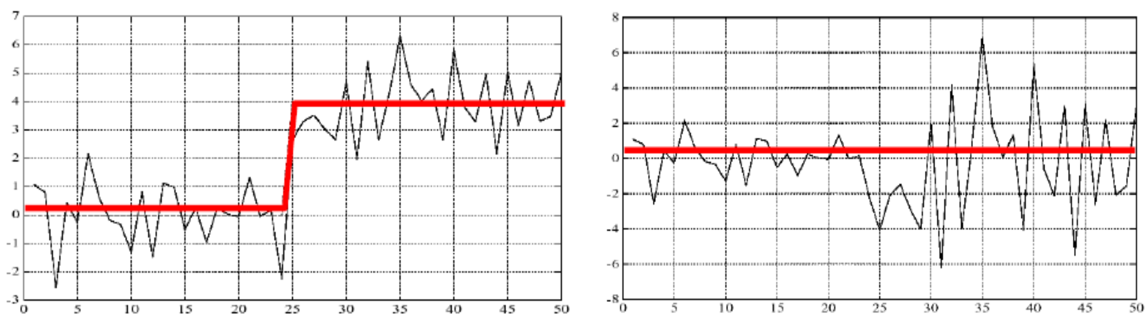
The Structural Condition Index (SCI) values are not uniform along a pavement section because of the variations in both the pavement structure and the subgrade soil condition. An average SCI score for a one-mile long pavement section based on individual SCI values obtained at multiple stations may not adequately capture the condition variability within the section, and could result in an incorrect assessment of the structural capacity of the pavement. A methodology characterizing the representative value of a section should account for these variations. The need to quantify such variability has lead to the use of the segmentation techniques in this research.

Homogeneous segments can be determined by identifying points at which, a change in the mean or variance of the dataset occurs [Sergio 2009]. The objective of this chapter is to propose a segmentation technique to characterize the representative SCI value of a pavement section. This chapter includes a brief discussion of the three segmentation methodologies to be considered. They are as follows:

- Cumulative Sums (CUMSUM);
- Absolute Difference in Sliding Mean values; and
- Cumulative Difference Approach (CDA).

5.2 SEGMENTATION METHODS

The main principle of a segmentation technique is to identify a homogeneous segment by analyzing changes in the mean or variance of the data series. The two basic scenarios that can be observed in a data series are: change in mean under a constant variance or change in variance under a constant mean. The borders of a homogeneous segment are usually identified by considering either one of two scenarios as shown in Figure 5.1.



(a) Mean changes and constant variance **(b) Variance changes and constant mean**

Figure 5.1 Type of changes in a data series [Sergio 2009]

5.2.1 Method I- Cumulative Sums (CUMSUM)

The Cumulative Sums (CUMSUM) method is based upon the comparison of the measured data with a target value. The user has the flexibility to choose the target value which can be an arithmetic mean of the dataset, threshold value, etc. Break points are created when the trend of the CUMSUM value changes [John 2005]. The following formula is used in this method:

$$CUMSUM_i = (CUMSUM_{i-1} - X_t) + X_i \tag{5.1}$$

Where:

X_t = Target value

X_i = Measured value of a data point

5.2.2 Method II-Absolute difference in sliding mean values

This method as illustrated in Figure 5.2 involves the smoothing of the data series which is followed by the data series analysis [Rubensam 1996]. The smoothing function is given as follows:

$$y_i = \frac{1}{2q+1}\sum_{i=i-q}^{i+q} x_i \tag{5.2}$$

Where:

y_i = Smoothed data

x_i = Measured data value

q = Number of neighboring elements to be weighted

The absolute differences are then calculated between the "*d*" neighbors contained in the smoothed function. It should be noted that this method does not give any guidelines about the "*d*" window.

$$z_i = |y_i - y_{i+d}| \tag{5.3}$$

Where:

z_i = Series of absolute difference

d = Number of elements between y_i and y_{i+d}

A threshold value, $z_{threshold}$ is then selected by the user, playing the role of a target value for the absolute difference series (z_i). The position of maxima in z_i above $z_{threshold}$, indicate the borders of the homogeneous segments.

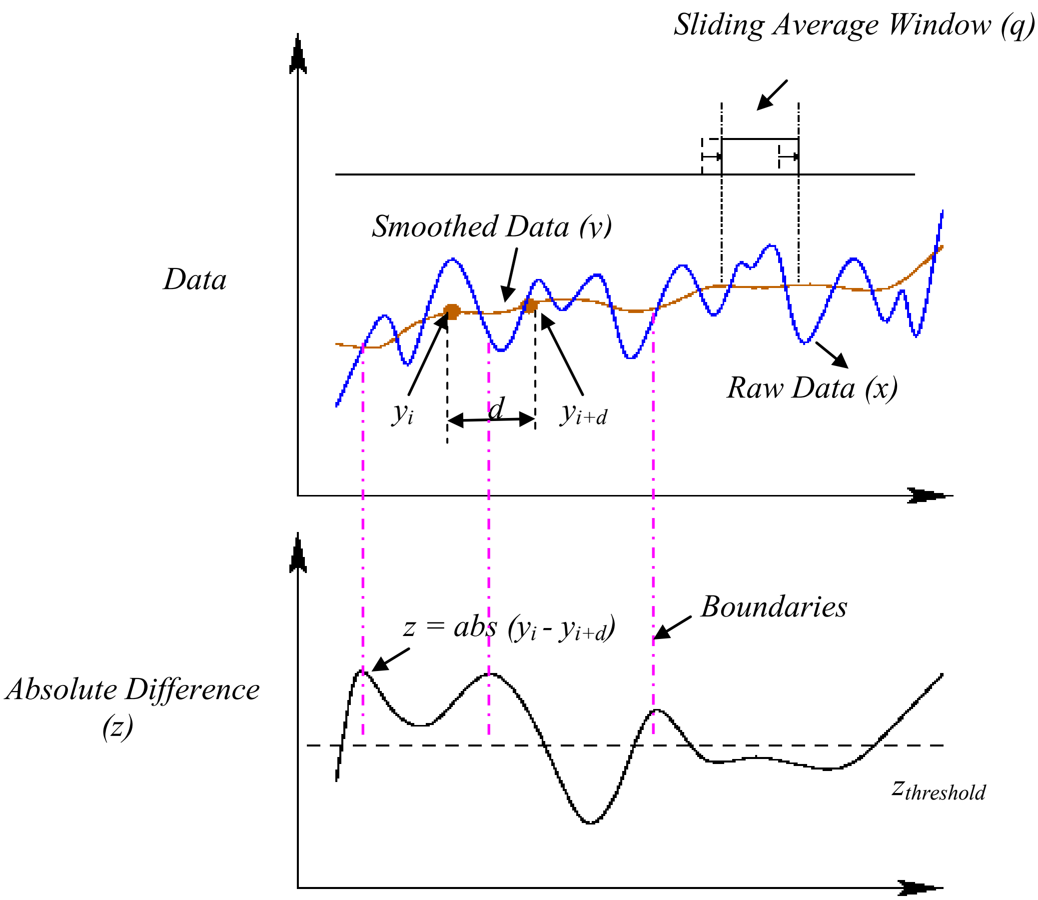


Figure 5.2 Graphical representation of the Absolute difference in sliding mean values method

5.2.3 Method III-Cumulative Difference Approach (CDA)

The Cumulative Difference Approach (CDA), as illustrated in Figure 5.3, is a graphical method which helps in the detection of the homogeneous segments [AASHTO 1986]. From the statistic Z_x, the difference between the cumulative area under the curve of a data series and the cumulative mean area is calculated, using equation 5.4. The homogeneous segment borders are defined by the points where the slope of Z_x changes its sign.

$$Z_X = \sum_{i=1}^{n} a_i - \left[\frac{\sum_{i=1}^{n} a_i}{L_p}\right]\sum_{i=1}^{n} x_i ; a_i = \left[\frac{r_{i-1} + r_i}{2}\right] x_i . \qquad (5.4)$$

Where:

x_i = Distance between an i^{th} data point and the first data point

n = n^{th} pavement response measurement

n_t = Total number of pavement response measurements

r_i = Value of the segmented characteristic of the pavement section

L_p = Total length of the pavement section

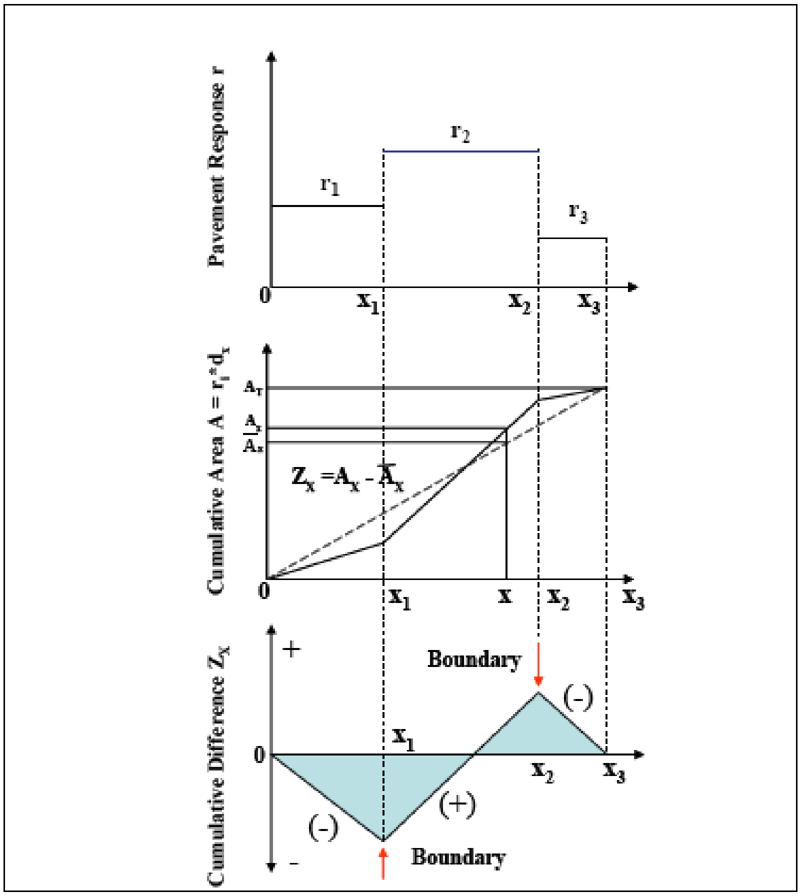


Figure 5.3 Graphical representation of the CDA method [AASHTO 1986]

5.3 ANALYSIS AND RESULTS

The focus of this chapter is to recommend a method to characterize the representative SCI value of a pavement section. As part of this process, the segmentation results obtained using the reviewed three methods were compared for the same pavement section. More detailed discussion of the segmentation analysis is presented in the following section.

5.3.1 Assumptions made in the segmentation analysis

In order to assist the segmentation analysis, assumptions about certain parameters used in the three segmentation methods are shown in Table 5.1.

Table 5.1 Assumptions of parameters used in the segmentation methods

<table>
<tr><th>Method</th><th>Parameter</th><th>Assumptions</th></tr>
<tr><td>CUMSUM</td><td>Target value</td><td>SCI threshold value of 1</td></tr>
<tr><td rowspan="3">Absolute difference in sliding mean values</td><td>Smoothing window (q)</td><td>3</td></tr>
<tr><td>Neighboring elements for absolute difference (d)</td><td>3</td></tr>
<tr><td>Threshold value</td><td>0.1</td></tr>
<tr><td>CDA</td><td>-NA-</td><td>-NA-</td></tr>
</table>

5.3.2 Comparison of the segmentation methods

A total of seven pavement sections were analyzed to compare the segmentation methods as listed in Table 5.2. Since the main principle of a segmentation technique is to identify a homogeneous segment by analyzing changes in the mean or deviation of the data series, the seven sections were chosen in such a way that different ranges of SCI average and standard deviation were included. This selection helped to ensure that the recommended segmentation method would perform well under all possible scenarios.

Table 5.2 Data used in the Segmentation analysis

Route	Environmental Zone	Subgrade Soil Category	Estimated 20-year ESALs	Total Pavement Thickness (inches)	SCI	
					Mean	Standard Deviation
US259 NB	Wet-Cold	Very Good	3,500,000	15.5	0.65	0.21
US259 SB	Wet-Cold	Very Good	2,438,000	16.1	0.84	0.26
FM 486	Mixed	Poor	1,082,000	7	0.19	0.02
FM 2199	Wet-Cold	Poor	1,404,000	9	0.3	0.06
SL 375 L1	Dry-Warm	Poor	2,798,000	13	0.52	0.14
US 69NB	Wet-Warm	Poor	10,719,000	17.5	0.32	0.08
SH 195	Mixed	Fair	10,385,000	16	1.73	0.36

Using the assumptions from Table 5.1, the homogeneous segments for each pavement section were determined using the three segmentation methods. Figure 5.4

shows the segmentation results obtained for one of the seven pavement sections, where the homogeneous segments are labeled as AB, BC to EF.

The average of a segment's SCI values was used to summarize the data of a homogeneous segment. To determine the effectiveness of each method, Standard Square Error (SSE) of the pavement section was computed using Equation 5.5. The results show that the CDA method gave the lowest error among all the three methods, indicating it as a reasonable method. Also, the CDA method requires no assumptions on any parameters required for the segmentation analysis, unlike the other two methods. Hence, it is recommended that the CDA method be used to characterize the representative SCI value of a pavement section in this research.

$$SSE = \sum_{j=1}^{m} \sum_{i=1}^{n} \left(\overline{X}_j - X_{ij} \right)^2 \tag{5.5}$$

Where:

$\overline{X}_j$ = Average SCI for a segment j

X_{ij} = SCI value for each i^{th} station in j^{th} segment

m = Number of homogeneous segments obtained by a segmentation method

n = Number of stations in a homogeneous segment

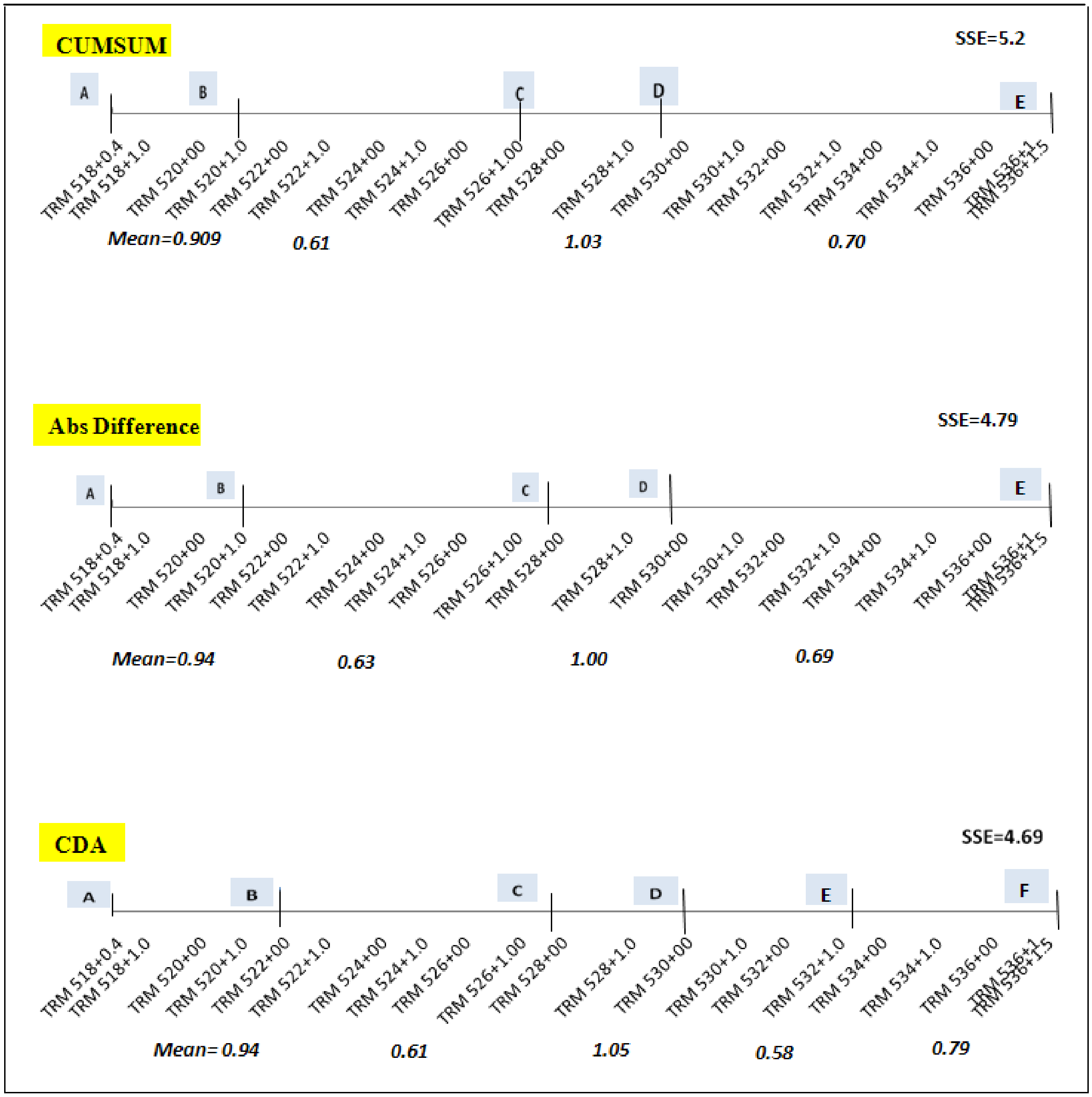


Figure 5.4 Comparison of the three segmentation methods

5.4 CONCLUSIONS

This chapter discussed the three reviewed segmentation methods for characterizing the representative value of a pavement section. The SSE of mean was adopted to determine the effectiveness of each method, and the results showed that the CDA method has the least SSE among the three methods. Moreover, the demerits of the CUMSUM method and the Absolute difference in sliding mean value method are that, these methods require assumptions regarding certain parameters due to the lack of guidelines. The CDA method, on the other hand, requires no such assumptions. Hence, in this research, it is recommended that the Cumulative Difference Approach (CDA) method be used to characterize the representative Structural Condition Index (SCI) value of a pavement section.

Chapter 6: SCI Threshold Analysis

6.1 INTRODUCTION

This chapter describes the SCI threshold analysis. The SCI threshold analysis was undertaken to develop guidance for the Maintenance and Rehabilitation (M&R) treatment category selection based on the corresponding SCI threshold values. In this chapter, the SCI values and other type of project-related data were evaluated by selected TxDOT pavement experts to determine which M&R treatment option or M&R treatment categories should be selected. The M&R treatment options include seal coat, thin overlay, etc., while M&R treatment categories include Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb) and Heavy Rehabilitation (HRhb).

6.2 THRESHOLD ANALYSIS APPROACH

As part of the SCI threshold analysis, expert opinions were used to evaluate the M&R treatment categories based on the corresponding SCI values and other project-related data. In this process, eight experts, having knowledge and experience in selecting M&R treatments based on an assessment of various types of project-level data, were requested to evaluate sixteen pavement sections which included around 153 half-mile PMIS sections.

6.2.1 Analysis Sheet

A total of 16 pavement sections along with their typical section information were stored in four separate spreadsheets, and were transmitted to the selected experts electronically for their evaluation. For each pavement section, the SCI values were summarized and graphically represented along with the homogeneous segments based on the Cumulative Difference Approach (CDA) method, as discussed in Chapter 5. The homogenous segments for a pavement section were labeled as AB, BC, CD, DE, and EF, as shown in Figure 6.1.

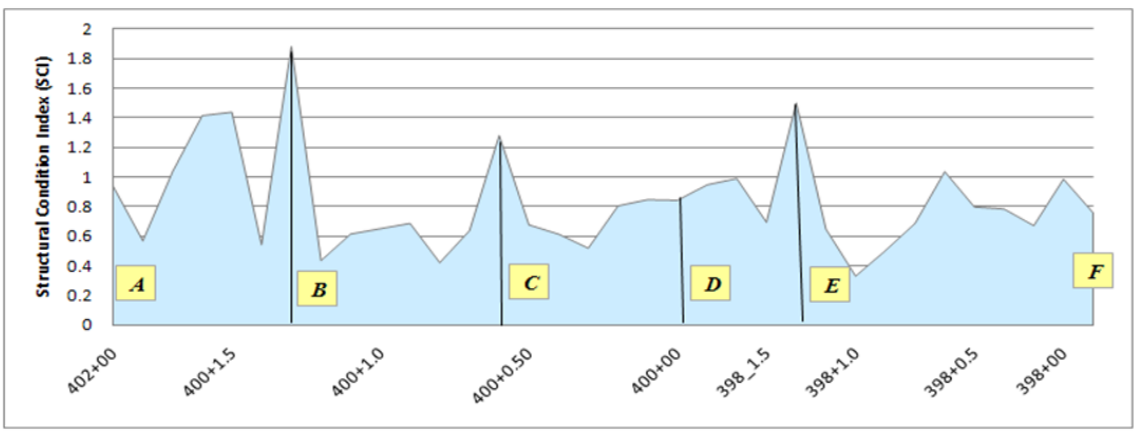


Figure 6.1 Homogeneous segments for a pavement section obtained from the CDA method

The spreadsheets, as shown in Table 6.1, included the pavement section information such as homogeneous segments obtained from the CDA method, section location, typical section, traffic data, FWD data, PMIS scores, soil type, soil modulus, Plasticity Index, and the Structural Condition Index (SCI). Additionally, the spreadsheet embedded documents like maps showing the FWD locations and any other details of the section, potentially useful to the pavement experts in their analysis.

The experts were requested to select an M&R treatment option (PM, LRhb, MRhb, HRhb) from a dropdown box provided in the spreadsheet, as shown in Table 6.1, by evaluating the data associated with each homogenous segment, with the assumption that the budget is not constrained. In addition, a "comment box" was included in the spreadsheet so that the experts recommend a specific M&R treatment option for each segment.

Table 6.1 SCI threshold analysis evaluation spreadsheets

Segment	AB	AB	BC	CD	CD	DE	EF	EF	EF
TRM	402+00	400+1.5	400+1.0	400+0.50	400+00	398+1.5	398+1.0	398+0.5	398+00
Segment Average SCI	1.12		0.58	0.80		1.04	0.72		
Distress Score	67	61	47	29	54	41	46	37	76
Ride Score	0.8	2.2	2.6	2.9	2.6	2.4	2.7	3.0	3.3
Condition Score	6	43	45	29	52	35	46	37	76
Current ADT	710	710	710	710	710	710	710	710	710
Future ADT	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
20 Year ESALs	607000	607000	607000	607000	607000	607000	607000	607000	607000
% Trucks	23.9%	23.9%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%
Trucks per Day	170	170	200	200	200	200	200	200	200
ATHWLD	10700	10700	10700	10700	10700	10700	10700	10700	10700
Speed Limit	70	70	70	70	70	70	70	70	70
ROW Width	100	100	100	100	100	100	100	100	100
Nr Thru Lanes / Dir	1	1	1	1	1	1	1	1	1
Right Shldr Width	4	4	4	4	4	4	4	4	4
Functional Class	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector
Soil Type Unified	CL	CL	CL	CL	CL	CL	CL	CL	CL
Soil Type AASHTO	A-6	A-6	A-6	A-6	A-6	A-4	A-4	A-6	A-6
Soil Description	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Plasticity Index	11 - 25	11 - 25	11 - 25	11 - 25	11 - 25	9 - 23	9 - 23	11 - 25	11 - 25
Liquid Limit	23 - 40	23 - 40	23 - 40	23 - 40	23 - 40	24 - 43	24 -43	23 - 40	23 - 40
Distress observed									
M& R Options		Do Nothing PM LRhb MRhb HRhb							
Comment Box (eg. Description of your pavement repair recommendation)									

6.3 ANALYSIS AND RESULTS

The eight experts, after completing the M&R treatment category selections and documenting the M&R treatment options for the 16 pavement sections, returned the completed spreadsheets. The survey results obtained from the experts were analyzed, and used as the basis for the SCI threshold recommendations.

6.3.1 Anomalies in M&R Treatment Options

The results showed that for the same homogenous segment, the selection of M&R treatment categories varied significantly from expert to expert. Sometimes, the same M&R treatment option is described for different M&R treatment categories. Some of the examples of the anomalies in M&R treatment options found in the SCI threshold analysis are shown in Table 6.2.

Table 6.2 Anomalies in M&R Treatment Options

M&R Treatment Categories	PM	LRhb	MRhb	HRhb
2" ACP overlay	X	X		
Repair failures, level up and seal		X	X	
Mill existing ACP and place minimum 3" overlay	X			
Mill existing ACP and place minimum 2" overlay		X		

6.3.2 Assumptions in the SCI threshold analysis

The focus of this chapter is to develop guidelines about the M&R treatment categories based on the SCI thresholds. To assist the analysis process, M&R treatment categories (PM, LRhb, MRhb, HRhb) were converted from linguistic terms to numerical scores as shown in Table 6.3, so that the average of all expert opinions could be used to determine the 'average M&R treatment category' for a homogeneous segment.

Table 6.3 Assumptions regarding the M&R treatment categories for the SCI threshold analysis

M&R Treatment Categories	Treatment Score
Do Nothing	0
PM	1
LRhb	2
MRhb	3
HRhb	4

As an example, for a homogeneous segment, if one expert selected as "Do Nothing" as the treatment and the rest of seven experts selected "PM" as the treatment, then, the 'average treatment score' in terms of the treatment options for the pavement segment is (0+1+1+1+1+1+1+1)/8 = 0.875. This 'average treatment score' was calculated for the rest of the segments as shown in Table 6.4.

Table 6.4 The SCI threshold analysis spreadsheet

H3 =(0+0+0+2+0+1+0+0)/8

	A	B	C	D	E	H	I	J
1							Stacey Young	Darlene Goehl
2	District	County	Route	TRM	SCI	Average Score (PMIS Treatment Level Score)	PMIS Treatment Level	PMIS Treatment Level
3	Lubbock	Hockley	FM 303	236+1.5	100	0.38	Do Nothing	Do Nothing
4	Lubbock	Hockley	FM 303	238+00	100	0.25	Do Nothing	Do Nothing
5	Atlanta	Harrison	FM 2199	278+0.5	28	3.50	MRhb	HRhb
6	Atlanta	Harrison	FM 2199	278+1.0	28	3.50	MRhb	HRhb
7	Atlanta	Harrison	FM 2199	278+1.50	34	3.63	MRhb	HRhb
8	El Paso	El Paso	SL 375	55+0.5	55	3.63	MRhb	MRhb
9	El Paso	El Paso	SL 375	56+0.9	55	3.50	LRhb	MRhb
10	El Paso	El Paso	SL 375	56+00	55	3.63	MRhb	MRhb
11	Laredo	Duval	SH 359	530+0.0	60	3.50	HRhb	MRhb
12	Wichita Falls	Wichita	US 82 Foam	510+0.2	113	3.63	HRhb	HRhb
13	Bryan	Brazos	FM 50 NB	416+00	27	1.88	LRhb	PM
14	Bryan	Washington	FM 50 SB	436+0.75	27	2.00	LRhb	Do Nothing
15	Bryan	Washington	FM 50 SB	436+00	27	2.00	LRhb	Do Nothing
16	Bryan	Brazos	FM 50 NB	414+0.0	28	2.38	LRhb	PM
17	Bryan	Brazos	FM 50 NB	414+0.5	28	2.13	LRhb	PM
18	Bryan	Brazos	FM 50 NB	414+1.0	28	2.38	LRhb	PM
19	Bryan	Brazos	FM 50 NB	414+1.50	28	1.88	LRhb	PM
20	Bryan	Brazos	FM 50 NB		28	2.38	LRhb	PM
21	Bryan	Washington	FM 50 SB	436+0.826 (RR)	28	2.00	LRhb	Do Nothing
22	Bryan	Washington	FM 50 SB	436+1.04	28	2.00	LRhb	Do Nothing
23	Bryan	Washington	FM 50 SB	436+1.14	33	2.00	LRhb	Do Nothing

In addition, assumptions regarding the 'average M&R treatment categories' for the corresponding 'average treatment scores' were made as shown in Table 6.5.

Table 6.5 Assumptions of average M&R treatment categories

Average Treatment Score	Average M&R Treatment Category
0.0-0.5	Do Nothing
0.5-1.5	PM
1.5-2.5	LRhb
2.5-3.5	MRhb
3.5-4.0	HRhb

6.3.3 Discussion of the two alternative methods for the SCI threshold analysis

The 'average treatment scores' and the SCI scores (multiplied by a factor of 100) for each pavement segment was plotted as shown in Figure 6.2. The average SCI value shown as the red dots in Figure 6.2, corresponding to each 'average M&R treatment category', was calculated. These averages were then joined using a straight line. The LRhb average based on the analysis results was 51. However, there were a large number of SCI values around 41 within this LRhb range. Therefore, a straight line was drawn through the other SCI averages to arrive at the proposed SCI for LRhb =65. Once the SCI average for each of the treatment designations was determined, two approaches were taken to determine the SCI thresholds.

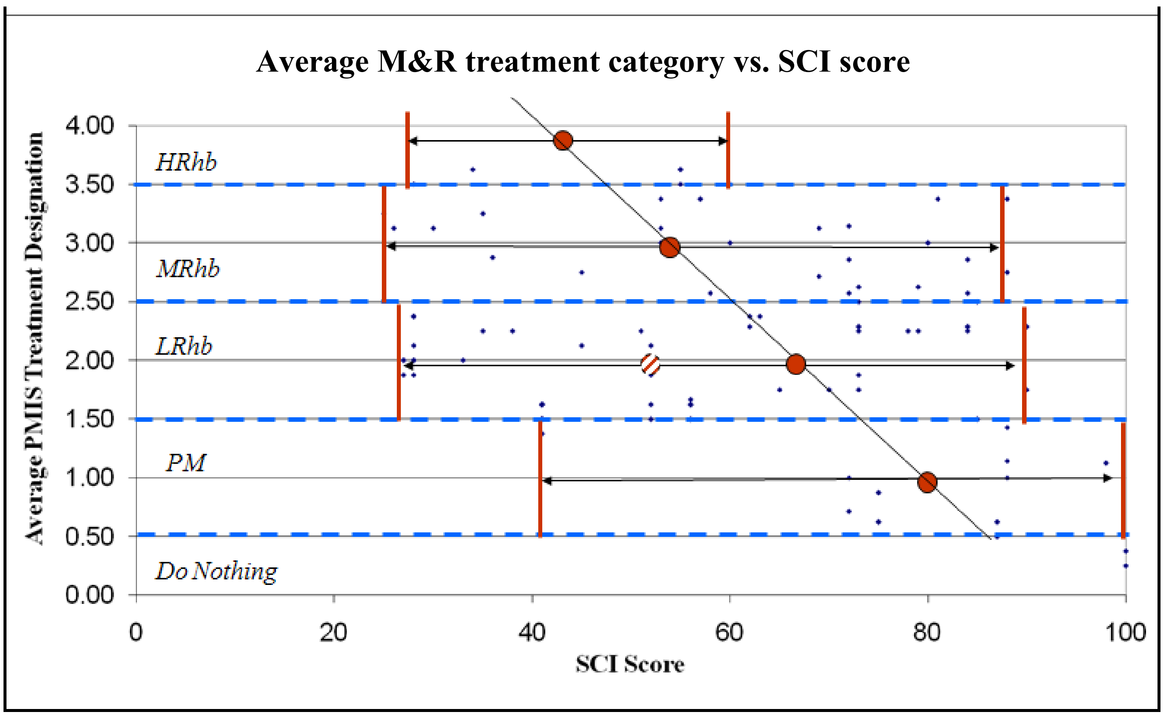


Figure 6.2 Average M&R treatment category vs. SCI score

Alternative Method 1:

The SCI averages, shown as the red dots in Figure 6.3, represent the boundaries for 'average M&R treatment category'. Considering the SCI score of 80 as the threshold value for " Do Nothing", the SCI thresholds can be established as follows: 80-100 as "Do Nothing", 65-79 as "PM", 55-64 as "LRhb", 45-54 as "MRhb" and 44 or lower as "HRhb". Using this categorization, an SCI score of 64 is assigned LRhb treatment level. However, using an engineering judgment, a pavement section that has a performance score of 64 indicates that it has lost more than half of its life, which suggests that the section requires a PMIS treatment level of MRhb or higher. This shortcoming of the developed SCI thresholds led to the Alternative method 2.

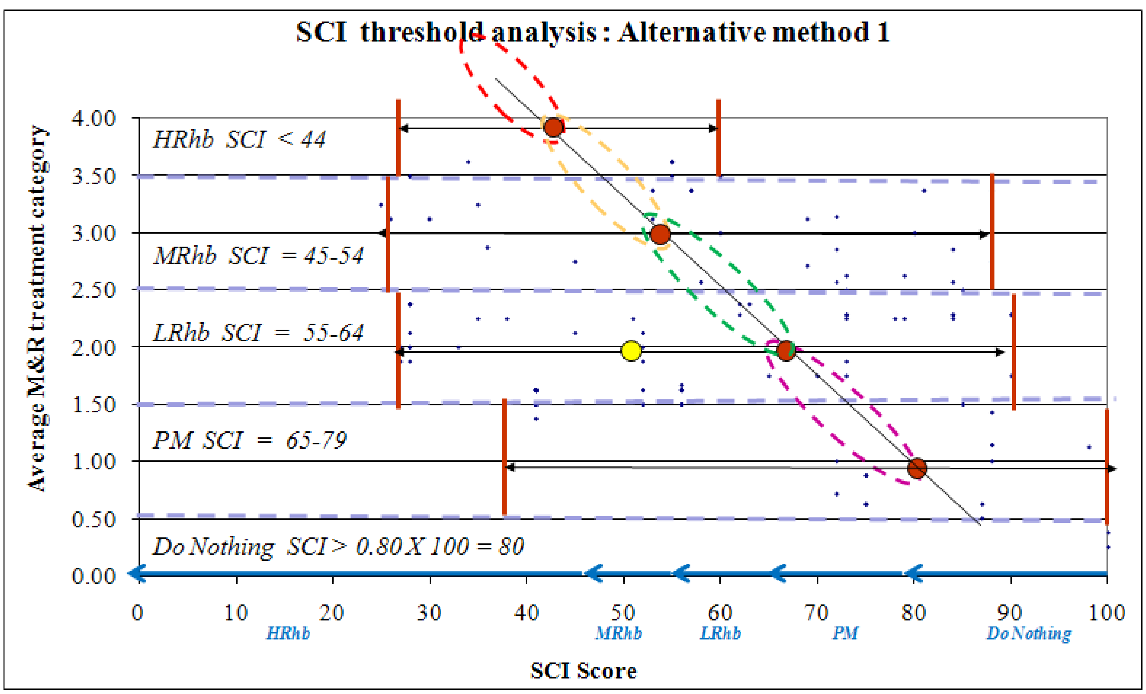


Figure 6.3 SCI threshold analysis using alternative method 1

Alternative Method 2:

In this case, the line formed by the four average values was extrapolated until it intersected the SCI score axis. This point of intersection gave the lower threshold value for the "Do Nothing" alternative. The SCI thresholds can be established as follows: 90 – 100 as "Do Nothing", 80 – 89 as "PM", 65 – 79 as "LRhb", 50 – 64 as "MRhb" and 49 or lower as "HRhb". Using this categorization, an SCI score of 64 is assigned MRhb treatment level, which is reasonable from an engineering point of view. Hence, results from the Alternative method 2 are recommended for the determination of the SCI thresholds in this research and are summarized in Table 6.6.

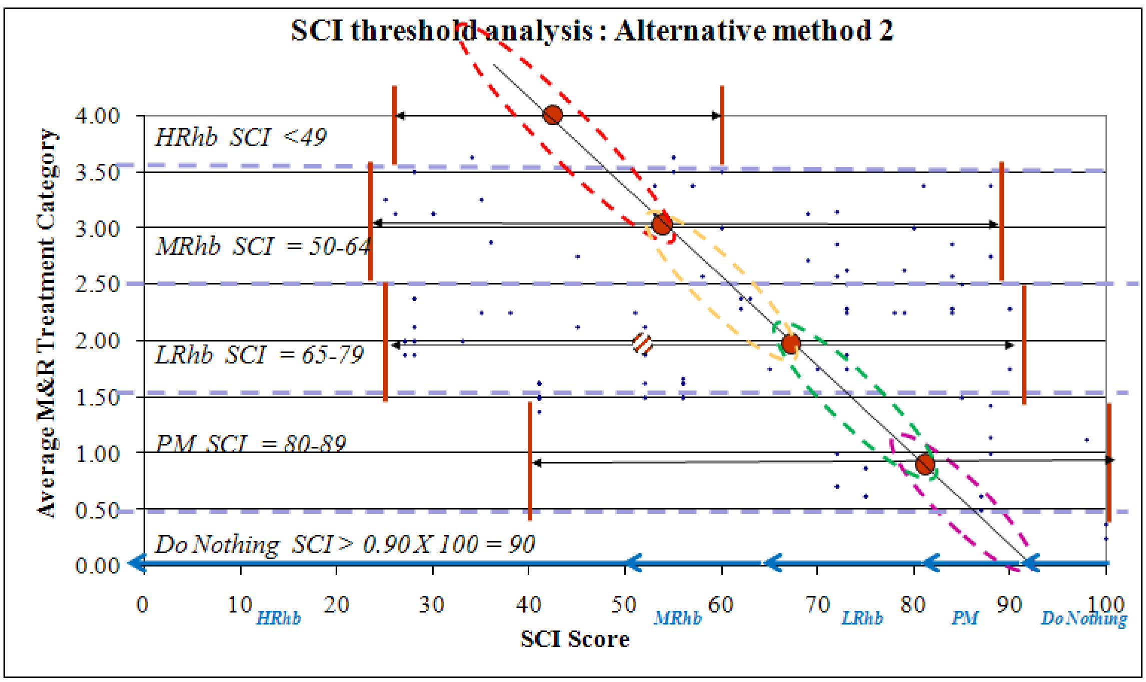


Figure 6.4 SCI threshold analysis using alternative method 2

Table 6.6 Recommended SCI thresholds

SCI Scores (SCI*100)	**M&R Category**
90-100	Do Nothing
80-89	PM
65-79	LRhb
50-64	MRhb
0-49	HRhb

6.4 CONCLUSIONS

This chapter discussed the process to develop the SCI threshold values for a particular M&R treatment category. The SCI threshold analysis results showed that the eight experts gave a wide range of specific M&R treatment options and M&R treatment categories, for the same pavement section information that was provided to them. The two alternatives for determining the SCI threshold values were also discussed. It should be noted that, the SCI scores cannot be correlated with the detailed M&R options, because the SCI is a network-level index and is not suitable for identifying specific M&R treatment options for a particular SCI. The SCI can only help select the M&R treatment categories at the project-level, and should be used along with detailed distress data and additional field tests such as the coring, the GPR, etc. to determine the specific M&R treatments.

Chapter 7: Determination of FWD Testing Spacing

7.1 INTRODUCTION

One of the major issues in the pavement management is the high cost of FWD data collection for determining the structural condition of a pavement at the network level. These include operational costs associated with the Falling Weight Deflectometer (FWD) and the traffic control. In addition, safety is another concern, especially on high -speed highways, due to the 'stop-and go' nature of the FWD deflection testing. Extensive research has been conducted to determine the ideal FWD testing spacing for adequately characterizing the pavement strength, while minimizing the cost and safety concerns. FWD pavement deflections are used by a number of agencies to evaluate pavement strength for project-level applications while a few agencies use the FWD pavement deflections for network-level applications. There is currently no specific TxDOT policy on the collection of pavement deflection data for network-level applications [TxDOT 2002]. Hence, this chapter discusses the ideal FWD test spacing required to characterize the structural condition of a pavement section using the Structural Condition Index (SCI).

7.2 ANALYSIS APPROACH

In the previous Project 0-4322 [Zhang 2003], the recommended frequency of FWD tests was two tests per half-mile section, using a risk-based method which controls the Type I error. In the current research, an analysis was conducted with the network-level SCI values to determine the FWD testing spacing by increasing the FWD testing spacing until it reaches a level at which the SCI value no longer provides a reasonably accurate assessment of the pavement section when compared to a complete set of project-level data. The analysis was accomplished in two ways:

- To create new datasets by randomly removing test points from the original project-level data; and
- To create new datasets by removing test points based on predetermined spacing that would result in approximately equally spaced test points.

7.2.1 Data used in the analysis

The SCI analysis is primarily based on the FWD deflections. In this research, the SCI analysis was conducted using FWD data collected on pavement sections for the project-level applications, such as pavement design support, load zone posting analysis and super-heavy load route evaluation. The FWD readings for these sections were collected at different test spacing to accommodate the project needs and local conditions. Some pavement sections were tested using equally spaced FWD measurement stations at 0.2, 0.1 miles, or smaller spacing, while in other cases FWD measurement stations were randomly spaced.

A subset of pavement sections containing SCI values, computed using the FWD data collected at approximately 0.1-mile spacing were first selected, providing a dataset which could be modified by increasing the FWD test spacing to 0.2, 0.25, 0.3, 0.4 or 0.5 miles as shown in Figure 7.1. This approach was used to obtain a total of seven project-level pavement sections for the analysis. The random removal of test points was achieved using a random number generator to avoid any potential bias.

As an example, if there are a total of 40 data points in a pavement section with FWD data collected at 0.1-mile equal spacing, then, the dataset with FWD data at equal spacing of 0.2-mile has 20 points. Since the average spacing (0.2 mile in this example) for the equal and random spacing datasets is the same, the number of data points (20 in this example) in both the datasets should be the same. Hence, the dataset for random spacing is obtained by randomly choosing 20 points from the 0.1-mile dataset.

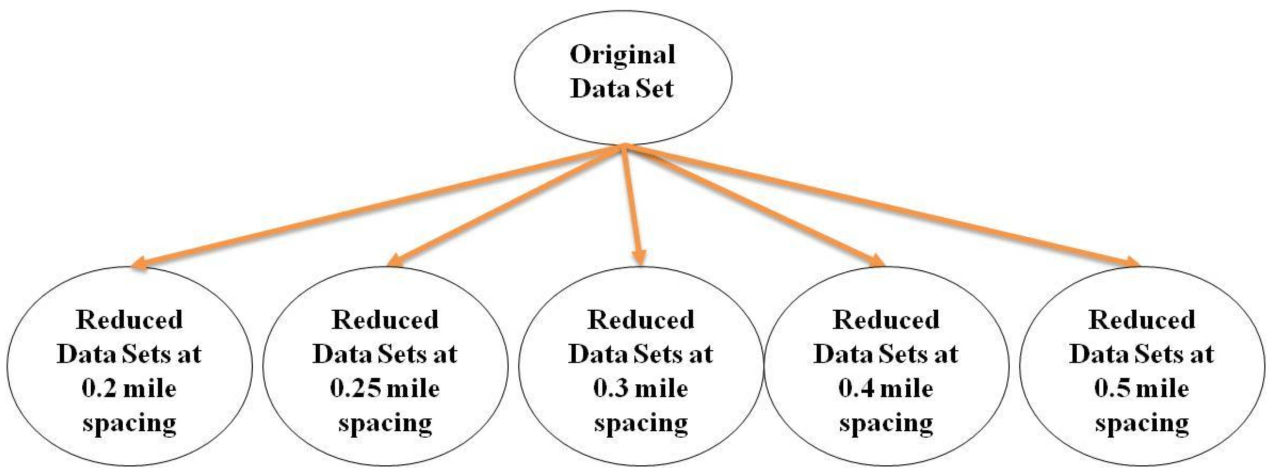


Figure 7.1 Data used in the analysis

7.3 DISCUSSION OF THE RESULTS

The original dataset was modified by removing data points randomly or systematically to create a series of new datasets with reduced data points at different test spacing. The results obtained using the Cumulative Difference Approach (CDA) method (Chapter 5) for the original dataset were used as a reference to compare the results from the reduced datasets. The cumulative difference (z) trends and segmentation results, for the original and reduced datasets, are discussed in this section.

7.3.1 Trend analysis

The intention of the trend analysis was to visually compare the cumulative difference (z) trends between the original and the reduced datasets. Since break points are created from the change in cumulative difference (z) trends, this visual comparison helps in anticipating whether the segmentation from the reduced dataset is similar to that of the original dataset.

Figures 7.2 and 7.3 show the results obtained for one of the seven sections used in the analysis. It can be seen that with larger station spacing of 0.4 miles, the trend of cumulative difference (z) curve hardly follows the original dataset. The results indicated that 0.2-mile spacing and 0.25-mile spacing give a representation close to the original data.

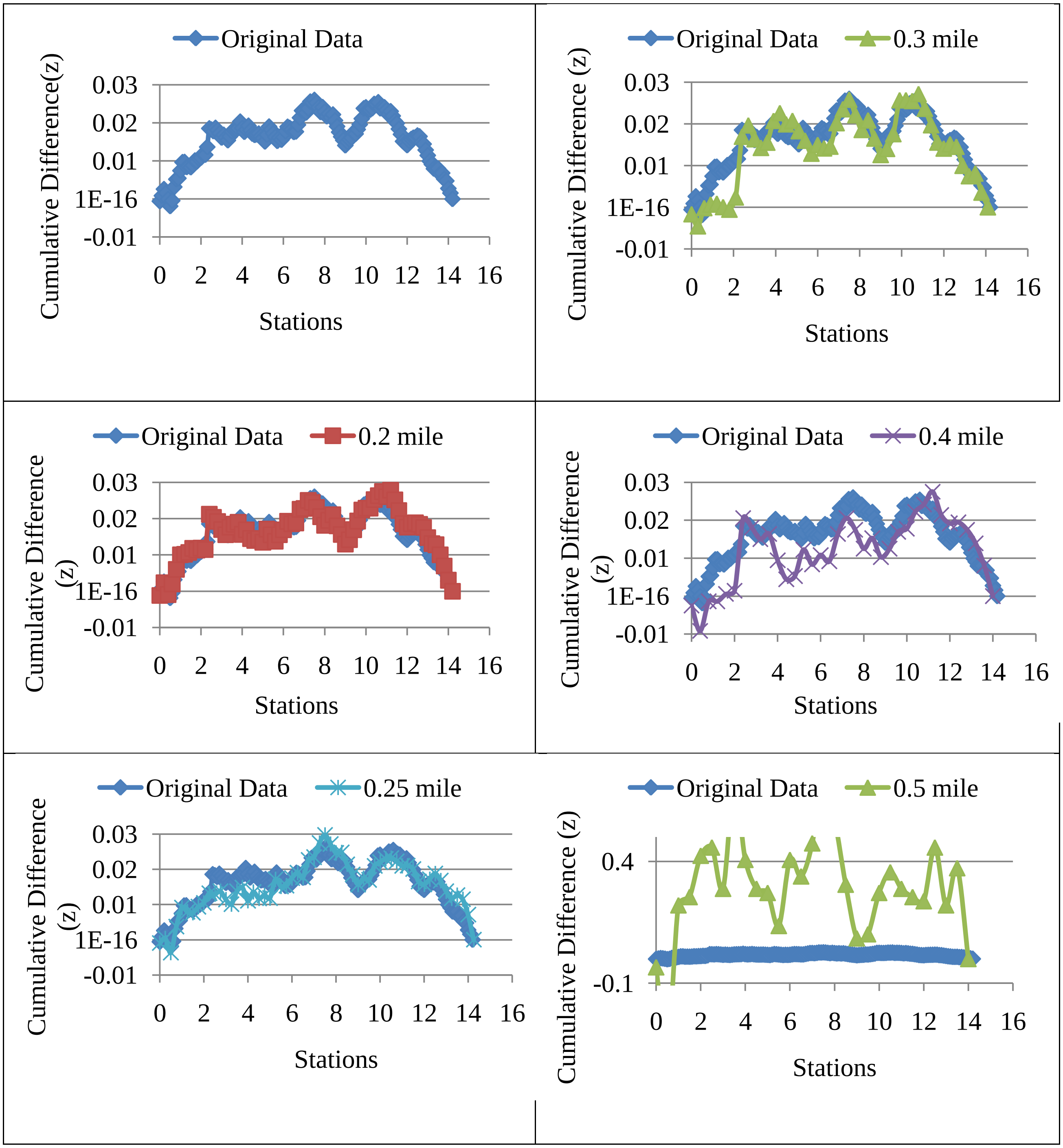


Figure 7.2 Comparison of cumulative difference (z) trends of original & reduced datasets with FWD data at equal spacing

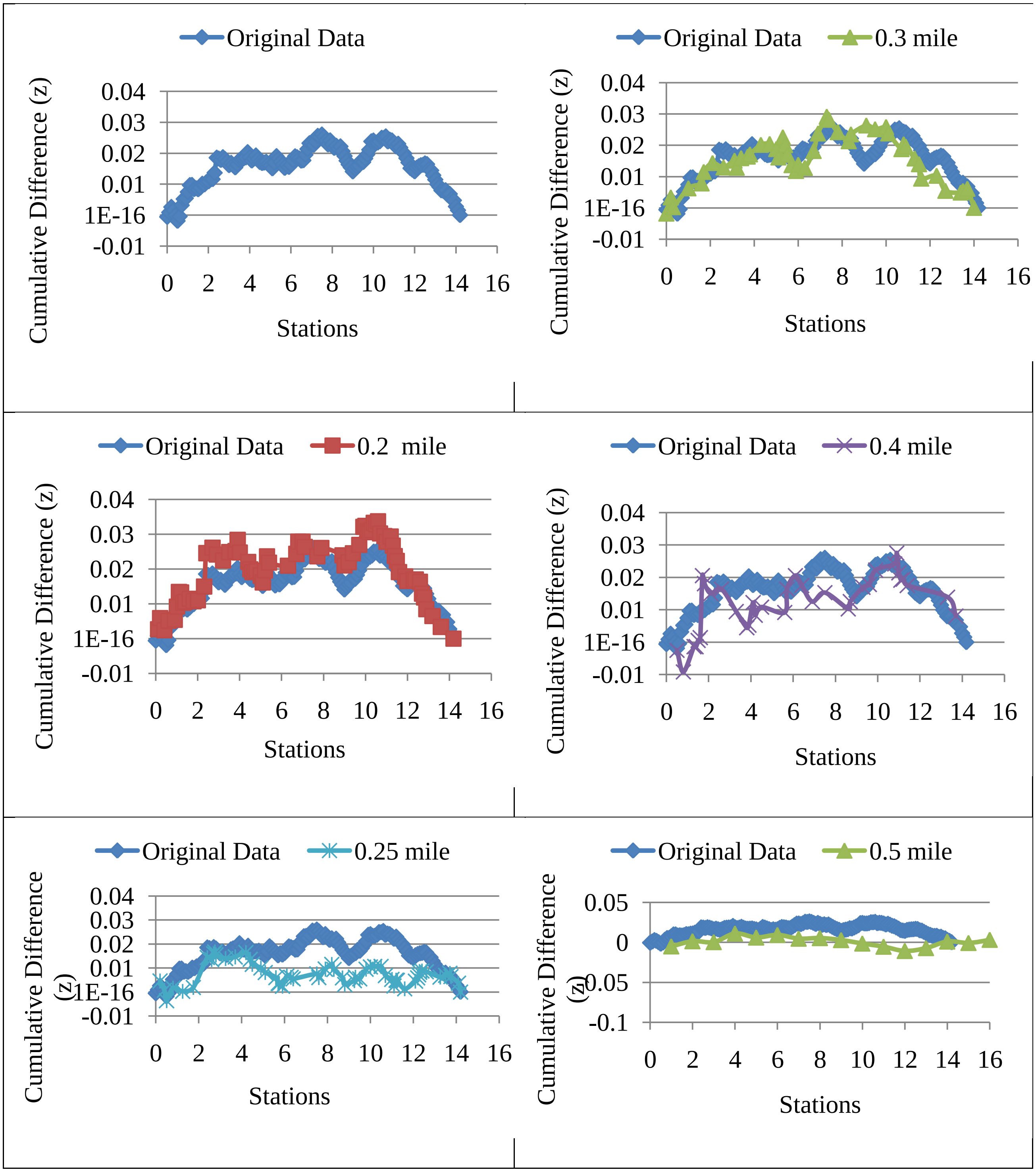


Figure 7.3 Comparison of cumulative difference (z) trends of original & reduced datasets with FWD data at random spacing

7.3.2 Segmentation results

The new datasets created with FWD data at 0.2-mile spacing and 0.25-mile spacing were considered for comparison of the segmentation results as shown in Figure 7.4. A comparison of the number of homogenous segments between the original dataset and new datasets was used in determining the optimal FWD testing spacing.

Figure 7.4 shows that 8 homogeneous segments labeled as AB, BC to HI were obtained from the CDA method for the original dataset.FWD data with 0.2-mile equal spacing was the closest dataset with 7 homogeneous segments. On the other hand, datasets with 0.2-mile random spacing, 0.25-mile random spacing, and 0.25-mile equal spacing were divided into 6 homogenous segments. Since the segmentation results for the original dataset are closest to the dataset with 0.2-mile equal spacing, a 0.2-mile equal spacing is recommended as the ideal FWD testing spacing for the SCI analysis.

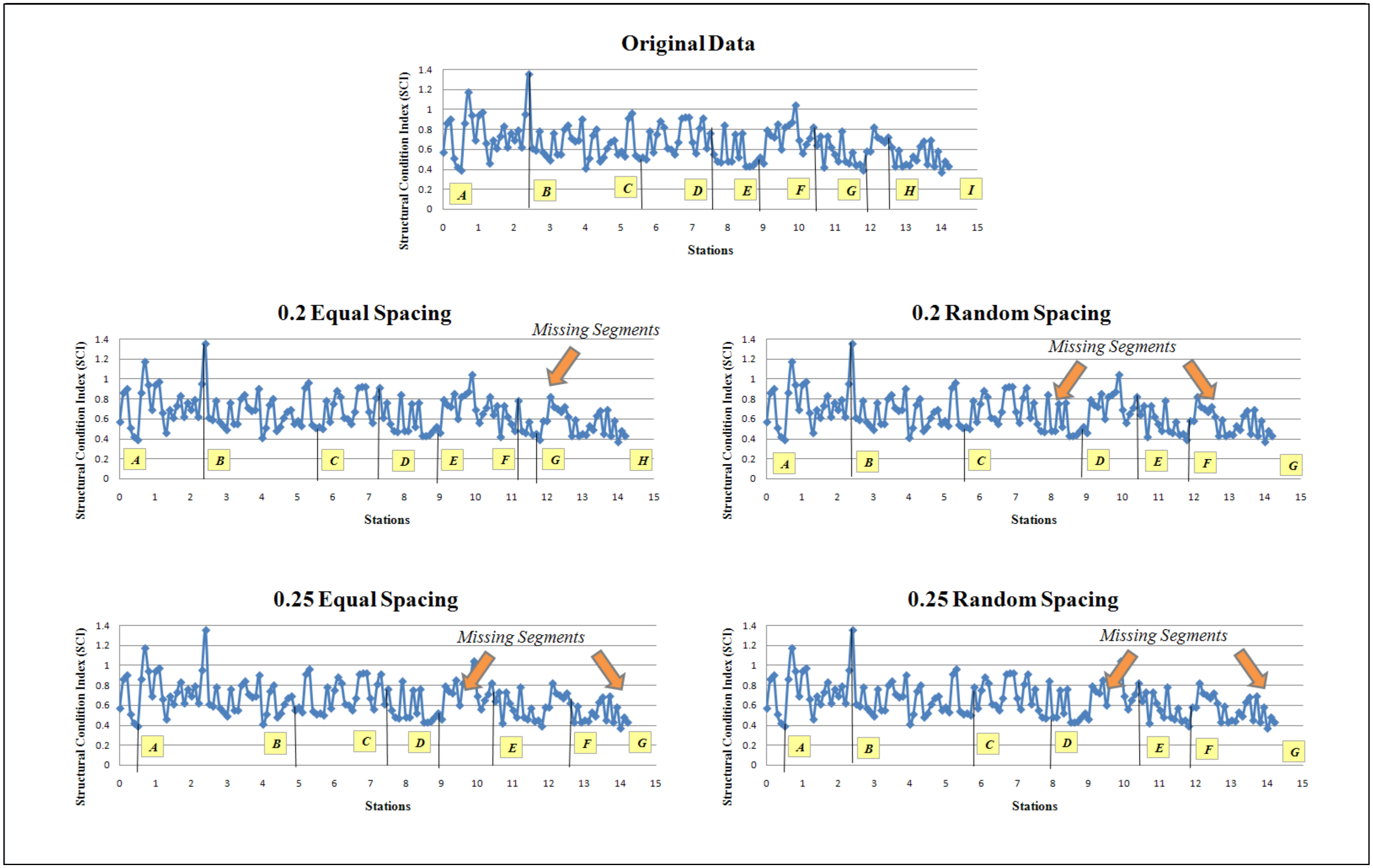


Figure 7.4 Comparison of segmentation results for the original and the reduced datasets

7.4 RECOMMENDATIONS ON TESTING SPACING

The analysis results indicated that the dataset obtained from 0.2-mile equal spacing compares well with the original dataset. Hence, the FWD data collected at test spacing of 0.2 miles is recommended for the SCI analysis. The FWD testing at 0.25-mile spacing can be recommended as a second alternative for the SCI analysis. This is because that the FWD testing at 0.2-mile spacing will not coincide well with the PMIS section lengths of 0.5 miles. However, the FWD testing at 0.25-mile spacing will achieve a standard test pattern in relation to the PMIS section (beginning, middle, end) as shown in Figure 7.5.

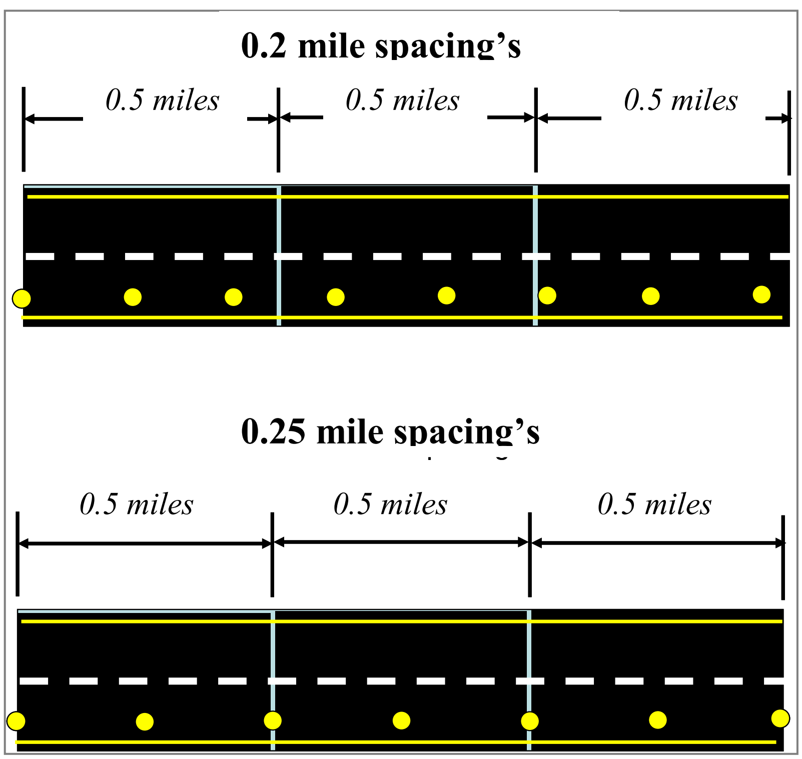


Figure 7.5 Comparison of FWD testing spacing at 0.2 mile and 0.25 mile

Chapter 8: Conclusions and Recommendations

The primary goal of this research is to validate the Structural Condition Index (SCI) method, and to develop guidelines for implementing the SCI at the network level. The scope of the research covered only flexible pavements in Texas. This chapter presents the conclusions drawn from this research and the recommendations for future work.

8.1 CONCLUSIONS

Conclusions drawn from this research are as follows:

- A literature review was undertaken to identify research on the state-of-the-art for structural indices at the network level. It was found that most of the agencies adopted either the Falling Weight Deflectometer (FWD) or the Ground Penetrating Radar (GPR) for structural evaluation of pavements at the network level. The FWD data collection requires traffic control and both methods require data collection and analysis personnel as well as other resources, resulting in high data collection costs. The evaluation methods, on the other hand, did not uncover any new structural indices or new information that could help improve the SCI method.
- The pavement mechanistic analysis responses such as the stress, strain and deflections, estimated from the WESLEA program were used in the SCI validation process. These responses were used to derive the percent-remaining-life factors, analogous to the SCI, from the Asphalt Institute (AI) fatigue and

rutting equations. The percent-remaining-life factors were called fatigue and rutting ratios respectively in this research. A non-linear regression analysis conducted with these ratios and the SCI values show that a correlation exists, indicating that the SCI method provides rational results.

- In addition to the SCI evaluation, an analysis was conducted to determine the effect of shallow bedrock depth on the SCI values. This is because that the SCI calculations are based on the FWD deflection data without considering the bedrock depth. Due to the lack of data collected on in-service pavement sections with different bedrock depths, the NETFWD database was used in this analysis. The NETFWD database was developed as part of a previous research and has information on modeled pavement structures with bedrock depths ranging from 40” to 720”. The analysis results show that the SCI values tend to decrease as bedrock depth increases all other factors remaining constant. As an example, the results indicate that the thin and intermediate pavement structures on a weak subgrade over shallow bedrock depths are structurally sound; however, the same pavement structures are found to be structurally inadequate at higher bedrock depths.
- This research recommends the use of a segmentation technique called the Cumulative Difference Approach (CDA) method to characterize the representative SCI value of a pavement section. The CDA method employs changes in the mean of a data series to identify the homogenous segments in a pavement section.

- A survey was conducted with eight TxDOT pavement experts to determine the SCI threshold values for M&R treatment categories. The experts were requested to select an M&R treatment category by evaluating the SCI values and other types of project-related data. These data were provided for each homogeneous segment in a pavement section, and the experts requested to select the M&R treatment category with the assumption that the budget is not constrained. The survey results were analyzed and used as the basis for the SCI threshold recommendations. The recommended SCI threshold values for each M&R treatment category in this research are as follows: SCI scores between 0.9 – 1.0 as "Do Nothing", 0.80 – 0.89 as "PM", 0.65 – 0.79 as "LRhb", 0.50 – 0.64 as "MRhb" and 0.49 or lower as "HRhb".
- An analysis was conducted using the CDA method to determine the ideal FWD testing spacing for the SCI analysis. This is because an ideal FWD testing spacing will help in minimizing data collection costs without reducing the accuracy of the pavement structural condition assessment. From the analysis results, this research recommends that the FWD data should be collected at test spacing of 0.2-miles for the SCI analysis.
- An SCI algorithm tool was developed to assist TxDOT with the implementation of the SCI for network-level applications. This tool was developed using Visual Basic Applications (VBA) in a macro-enabled excel workbook, and is an interface between the SCI methodology and the users. The tool allows the user to input the

required data, run the algorithm and view the SCI analysis results for a pavement section.

- The SCI analysis is based on the SN_{req} table created from discussions with the Project Director in this research. To allow more flexibility, the SCI algorithm tool incorporates the ability to create custom SN_{req} tables which allows TxDOT districts to customize according to their needs.
- A user manual was also developed to explain the SCI algorithm tool which specifically addresses and gives necessary guidelines on how the SCI analysis results can be used to evaluate the structural condition of a pavement section.

8.2 RECOMMENDATIONS

Recommendations for further research are as follows:

- The SCI analysis uses total pavement thickness information. Hence, a pavement layer thickness and material type database should be developed for the Texas PMIS in order to fully implement and automate SCI at the network level. Also, a methodology for incorporating pavement treatment history information in the PMIS database should be developed to ensure that the pavement layer thickness and material type database is kept current.
- Since the SCI values are affected by the shallow bedrock depths, an algorithm that considers the effects of shallow bedrock depth on the SCI values should be developed and incorporated in the SCI analysis.

- Further work is needed to supplement the SCI with the development of a ‘Deep Distress’ index which uses the PMIS data. The SCI values can be estimated by a regression on the ‘Deep Distress’ index when the FWD deflections for pavement sections are not available. Since it may be impractical to collect a 100% FWD data sample of the TxDOT roadway network due to cost and time considerations, the ‘Deep Distress’ index could be used as a surrogate estimate of pavement structural condition for pavement sections without FWD data. This approach would provide a 100 % sample of pavement structural condition assessment that can support state-wide implementation of the SCI method.
- Further work is needed to evaluate inclusion of the SCI method in the pavement preventive maintenance and rehabilitation ranking procedure, for the development of program of projects in the district 4-year pavement management plan.
- Further work is needed to modify and evaluate the SCI method for use on rigid pavements as this research focuses on evaluation of the SCI method for flexible pavements only.
- The efficiency of the SCI algorithm can be improved by developing temperature correction factors for the SCI values. The current SCI algorithm tool facilitates this improvement by allowing the user to input variables such as the FWD deflection testing time, and the pavement, air and surface temperature data.
- An automated segmentation procedure using the CDA method should be developed in the SCI algorithm tool for determination of the representative SCI value of a pavement section.

- Further automation can be achieved by incorporating an FWD parsing code in the SCI algorithm tool which will directly read the values from a raw FWD file, eliminating the need for the user to manually input the FWD data.
- Upon development of the layer thickness database, and bedrock depth algorithm, further enhancements can be achieved by developing a master algorithm that automates the SCI analysis process for an entire county, district or statewide network without the need for further human interaction.

Appendix A

Matrix Chart

ENVIRONMENTAL ZONE

MIXED

SUBGRADE / TRAFFIC	VP	P	P	F	F	G	VG	VG	VG
VERY LOW		127		28,21,178	125,169,177	22, 44, 45,134, 143,179, 180	64,131	18, 41, 42, 46,128, 133, 135, 136	176
				117,132		124	144	145, 146, 147	
LOW			120	167,175	122	123,151	126	171	172
			19,121	25,152	24, 33 & 34	130	31,129,137,166	29 , 30, 118, 119	173, 174,
MEDIUM			39	40		170	148,149,150		
							181,182		
HIGH						154	168	1,8,9,153, 155	
VERY HIGH		157,158, 159,160		163,164		162	165	161	

WET-WARM

SUBGRADE / TRAFFIC	VP	P	P	F	G	G	VG
VERY LOW	114	43, 47	2	4		16,110,138,139	65, 66, 67, 68,142
	5	113		115, 116			141
LOW				101, 102		140	
				12			14
MEDIUM			17				
HIGH		54	15	55, 56, 59, 61	57, 60	13	58
VERY HIGH							

WET-COLD

SUBGRADE / TRAFFIC	VP	P	F	G	VG	VG	VG
VERY LOW	108	38	69	70			
		107, 109		106			
LOW					111, 112	105	
		6					10 & 11
MEDIUM		51		104	72	52, 53	32
HIGH							
VERY HIGH							

DRY-WARM

SUBGRADE / TRAFFIC	VP	P	P	F	G	VG	VG	VG
VERY LOW			91	73, 75, 76, 77, 78	74, 79	80	87, 93	94
				100				
LOW								
		81, 82	49, 50	89	98			
MEDIUM		88		84, 85				
HIGH			83		86			7
VERY HIGH								

DRY-COLD

SUBGRADE / TRAFFIC	VP	P	F	G	G	VG
VERY LOW		95, 96, 97	48	37	20	3
			103	156		
LOW						
		62, 63				
MEDIUM			35 & 36			32, 71
HIGH						
VERY HIGH						

SECTION NO

Appendix B

List of 180 sections

Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
1	Austin	Williamson	SH 195	Mixed	Fair	10,385,000	5.921	Yes	No	No	Yes & GPR	72
2	Houston	Galveston	FM 3436	Wet - Warm	Very Poor	467,000	1.568	No	No	No	Description	140
3	Abilene	Taylor	FM 89	Dry - Cold	Very Good	607,000	4	No	No	Yes	From DCP Data	60
4	Beaumont	Hardin	FM 1293	Wet - Warm	Fair	531,000	0.5	No	Yes	No	Description & Cores	140
5	Corpus Christi	Nueces	FM 1694	Wet - Warm	Very Poor	577,000	3.7 (3 pads)	No	No	Yes	From DCP Data	110
6	Atlanta	Harrison	FM 2199	Wet - Cold	Poor	1,404,000	4	No	No	No	Plans	140
7	Odessa	Ward	IH 20	Dry - Warm	Very Good	22,625,000	10.9 (gaps in data)	No	Yes	No	scription, cores and	120
8	Austin	Travis	SH 71 EB	Mixed	Very Good	10,438,000	4.31	No	No	No	Plans	170
9	Austin	Travis	SH 71 WB	Mixed	Very Good	11,247,000	5.75	No	No	No	Plans	148
10	Atlanta	Upshur	US 259 NB (A)	Wet - Cold	Very Good	3,500,000	3.2	No	Yes	No	Plans and cores	140
11	Atlanta	Upshur	US 259 SB (B)	Wet - Cold	Very Good	2,438,000	4	No	Yes	No	Plans and cores	140
12	Beaumont	Orange	FM 1442	Wet - Warm	Fair	1,396,000	2.8	No	No	No	Description	125
13	Beaumont	Hardin	US 69 Lumberton	Wet - Warm	Good		30 feet	No	No	Shoulder only	Description	140
14	Beaumont	Tyler	US 69 Woodville	Wet - Warm	Very Good	8,033,000	6.6	No	Yes	Yes	cription, cores and	140
15	Beaumont	Jefferson	US 69 NB ML near District Office	Wet - Warm	Poor	10,719,000	1000 feet	Yes	No	Yes	scription, GPR and D	140
16	Beaumont	Newton	SH 87 NB	Wet - Warm	Good	839,000	6.6	Yes	No	No	Description, GPR	240
17	Beaumont	Jefferson	SH 82 SB	Wet - Warm	Poor	3,814,000	2	Yes	Yes	No	Description, GPR	300+
18	Bryan	Brazos	SH 47 EB	Mixed	Very Good	993,000	6.6	No	No	No	Description	200
19	Bryan	Milam	FM 486	Mixed	Poor	1,082,000	1.75	No	No	No	Description	180+
20	Lubbock	Floyd	FM 97	Dry - Cold	Good	99,000	18	No	No	No	Description	70
21	Austin	Williamson	FM 112	Mixed	Fair	874,000	15	No	No	No	Description	300+
22	Austin	Williamson	FM 619	Mixed	Good	577,000	2.5	No	No	No	Description	250+
23	Austin	Travis & Williamson	FM 973 NB	Mixed	Fair	2,650,000	16.1	No	No	No	Plans	150+
24	Austin	Williamson	FM 1660	Mixed	Fair	1,336,000	10.7	No	No	No	Description	200+

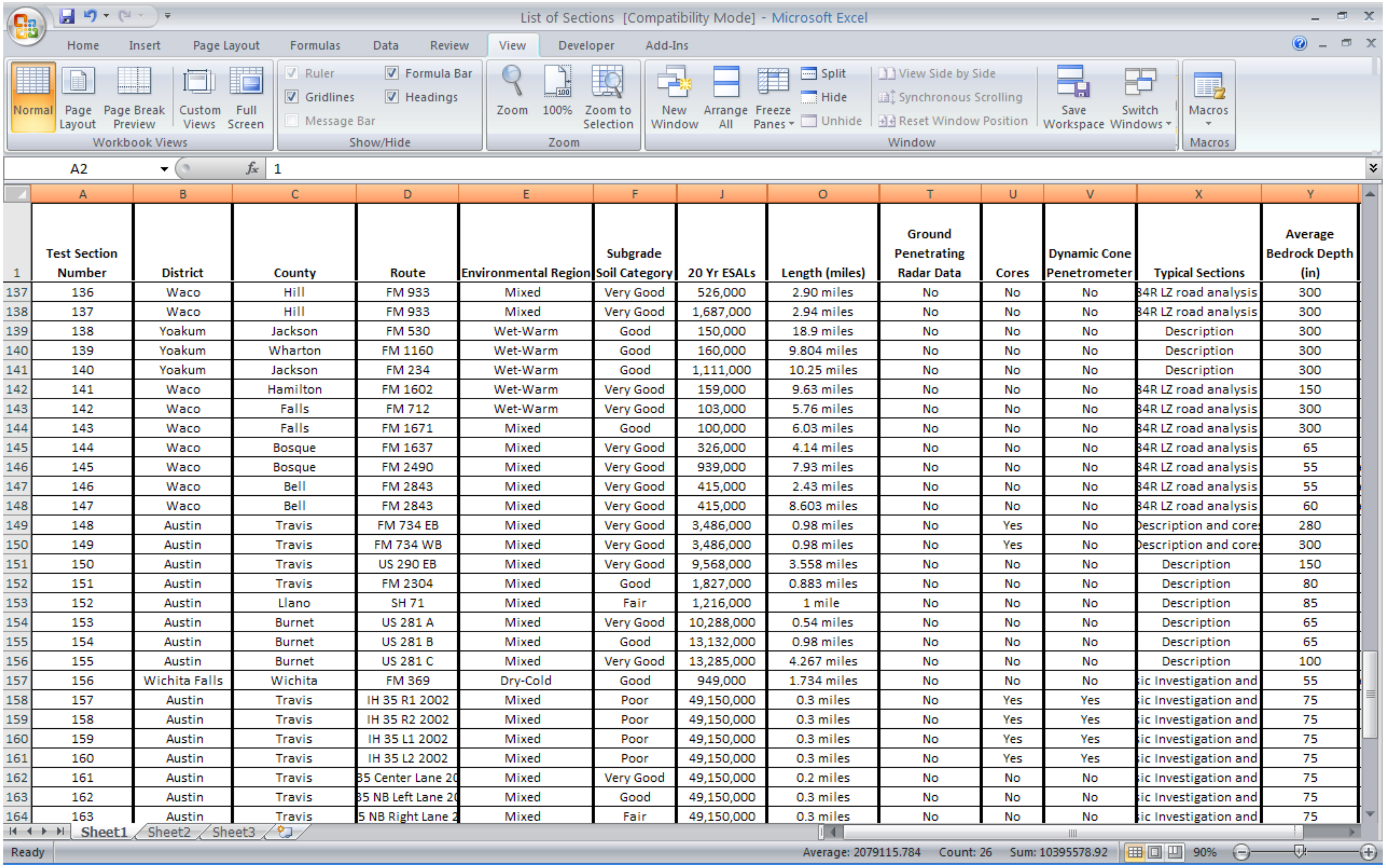
List of Sections [Compatibility Mode] - Microsoft Excel

	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
26	25	Austin	Williamson	FM 3349	Mixed	Fair	175,000	4	No	No	No	Description	170
27	26	Bryan	Washington	FM 50 SB	Mixed	Poor	669,000	1.14	No	No	No	Description	145
28	27	Bryan	Brazos & Burleson	FM 50 NB	Mixed	Poor	575,000	3	No	No	No	Description	140
29	28	Bryan	Brazos	FM 1687 EB	Mixed	Fair	202,000	2.9	No	No	No	Plans	300
30	29	Brownwood	Brown	US 67 NEB	Mixed	Very Good	5,000,000	2.9	No	Yes	No	Description & Cores	65
31	30	Brownwood	Brown	US 67 SWB	Mixed	Very Good	5,000,000	2.9	No	Yes	No	Description & Cores	100
32	31	Waco	Hill	FM 66	Mixed	Very Good	2,167,000	2	Yes	Yes	No	Description & GPR	200+
33	32	Atlanta	Titus & Morris	SH 49	Wet - Cold	Very Good	3,889,000	7.4	No	No	No	Description	40+
34	33	Austin	Travis	FM 1625 N	Mixed	Fair	1,405,000	4.6	No	No	No	Description	300+
35	34	Austin	Travis	FM 1625 S	Mixed	Fair	1,405,000	4.6	No	No	No	Plans	300+
36	35	Amarillo	Hartley	US 87 K1	Dry - Cold	Fair	4,318,000	14.2	No	No	No	Description	130
37	36	Amarillo	Hartley	US 87 K2	Dry - Cold	Fair	4,318,000	14.1	No	No	No	Description	130
38	37	Lubbock	Hockley	FM 303	Dry - Cold	Good	502,000	5.2	No	No	No	Description	60+
39	38	Dallas	Navarro	FM 1126	Wet - Cold	Poor	219,000	22.6	No	No	No	Description	140+
40	39	Bryan	Burleson	21 WB pads 22 23	Mixed	Poor	3,682,000	.9 miles	No	No	No	Plans	120 +
41	40	Bryan	Brazos	21 WB pads 28 29	Mixed	Fair	3,841,000	.9 miles	No	No	No	Plans	230+
42	41	Brownwood	Comanche	FM 1702 NB	Mixed	Very Good	350,000	2.8 miles	No	No	No	Description	300+
43	42	Brownwood	Comanche	FM 1702 SB	Mixed	Very Good	350,000	2.8 miles	No	No	No	Description	300+
44	43	Corpus Christi	Nueces	FM 2826	Wet - Warm	Poor	127,000	3.2 miles	No	No	No	Description	300+
45	44	Bryan	Brazos	SH 47 EB pad 5	Mixed	Good	993,000	500 feet	No	No	No	Description	200
46	45	Bryan	Brazos	SH 47 EB pad 6	Mixed	Good	993,000	500 feet	No	No	No	Description	200
47	46	Bryan	Brazos	H 47 EB pads 1, 2,	Mixed	Very Good	993,000	500 feet each pad	No	No	No	Description	300
48	47	Corpus Christi	Nueces	FM 1694 SB	Wet - Warm	Poor	408,000	6.6 miles	No	No	No	Plans	300
49	48	Amarillo	Randall	FM 2219	Dry - Cold	Fair	748,000	5.9 miles	No	No	No	Description	120
50	49	El Paso	El Paso	375 EB outside la	Dry - Warm	Poor	2,798,000	5.3 miles	No	No	No	Description	60+
51	50	El Paso	El Paso	375 EB inside la	Dry - Warm	Poor	2,798,000	12.4 miles	No	No	No	Description	60+
52	51	Ft. Worth	Johnson	M 917 WB 6-200	Wet - Cold	Poor	4,553,000	9.13 miles	No	No	No	Plans	100+

Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
52	Ft. Worth	Johnson	M 917 WB 7-200	Wet - Cold	Very Good	4,553,000	9.13 miles	No	No	No	Plans	170
53	Ft. Worth	Johnson	FM 916	Wet - Cold	Fair	332,000	0.60 miles	No	No	No	Plans	200+
54	Lufkin	Polk	US 59 F1	Wet - Warm	Poor	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
55	Lufkin	Polk	US 59 F2	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
56	Lufkin	Polk	US 59 F3	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
57	Lufkin	Polk	US 59 F4	Wet - Warm	Good	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
58	Lufkin	Polk	US 59 F5	Wet - Warm	Very Good	14,362,000	0.2 mile	No	Yes	No	Research Report 98	200+
59	Lufkin	Polk	US 59 F6	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
60	Lufkin	Polk	59 F0 1-1/2" surf	Wet - Warm	Good	14,362,000	0.1 mile	No	Yes	No	Research Report 98	90+
61	Lufkin	Polk	S 59 F0 3" surfa	Wet - Warm	Fair	14,362,000	0.1 mile	No	Yes	No	Research Report 98	120+
62	Wichita Falls	Archer	82 Foamed Asph	Dry - Cold	Poor	2,739,000	3 miles	Yes	Yes	Yes	ernal and ASCE repo	70+
63	Wichita Falls	Wichita	JS 82 Lime Treate	Dry - Cold	Poor	2,739,000	1 mile	No	No	No	ernal and ASCE repo	120+
64	Austin	Blanco	US 290 WB	Mixed	Very Good	1,340,000	0.15 miles	No	No	Yes	Description	90+
65	Houston	Harris	US 290 FR good	Wet - Warm	Very Good	2,404,000	0.3 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
66	Houston	Harris	US 290 FR bad	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
67	Houston	Harris	90 FR Bad Inside	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
68	Houston	Harris	0 FR Bad Outside	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
69	Ft. Worth	Jack	US 281 SB	Wet - Cold	Fair	2,404,000	0.29 miles	Yes	Yes	Yes	Research Report 181	55
70	Ft. Worth	Jack	US 281 NB	Wet - Cold	Good	2,404,000	0.29 miles	Yes	Yes	Yes	Research Report 181	55
71	Childress	Motley	US 70 / US 62 WE	Dry - Cold	Very Good	685,000	5.4 miles	No	No	No	Description	75
72	Ft. Worth	Hood	FM 51	Wet - Cold	Very Good	7,952,000	1.1 miles	No	No	No	Plans	300+
73	Pharr	Cameron	1479 test sectio	Dry - Warm	Fair	1,037,000	0.1 mile	No	No	No	Pavement Design	300+
74	Pharr	Cameron	1479 test sectio	Dry - Warm	Good	1,037,000	0.05 mile	No	No	No	Plans	300+
75	Pharr	Cameron	1479 test sectio	Dry - Warm	Fair	1,037,000	0.1 mile	No	No	No	Plans	300+
76	Pharr	Cameron	1 800 test sectior	Dry - Warm	Fair	1,220,000	0.1 mile	Yes	Yes	Yes	ic Investigation and	300+
77	Pharr	Cameron	1 800 test sectior	Dry - Warm	Fair	1,220,000	1.4 mile	Yes	Yes	Yes	ic Investigation and	300+
78	Pharr	Cameron	1 800 test sectior	Dry - Warm	Fair	1,220,000	0.1 mile	Yes	Yes	Yes	ic Investigation and	300+
79	Pharr	Cameron	FM 1419	Dry - Warm	Good	1,195,000	5.7 miles	No	No	No	ent Design & Forensic	300+

	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
81	80	Laredo	Duval	FM 1329	Dry - Warm	Very Good	473,000	8.5 miles	No	No	No	Plans	140+
82	81	Laredo	Webb	Loop 20 NB	Dry - Warm	Poor	5,117,000	1.9 miles	No	No	No	Plans	110+
83	82	Laredo	Webb	Loop 20 SB	Dry - Warm	Poor	5,117,000	1.8 miles	No	No	No	Plans	110+
84	83	Laredo	Webb	SH 359 EB	Dry - Warm	Poor	13,119,000	4.7 miles	No	No	No	Plans	75+
85	84	Laredo	Duval	59 NB @ San Dieg	Dry - Warm	Fair	3,633,000	1.5 miles	No	No	No	Plans	110+
86	85	Laredo	Duval	59 NB @ San Dieg	Dry - Warm	Fair	3,633,000	1.4 miles	No	No	No	Plans	110+
87	86	El Paso	El Paso	FM 1281 NB	Dry - Warm	Good	14,824,000	2.5 miles	No	Yes	No	and Core log spreads	80+
88	87	El Paso	Hudspeth	FM 1437 SB	Dry - Warm	Very Good	588,000	9.0 miles	No	Yes	No	Core log spreadsheet	92+
89	88	El Paso	El Paso	US 62 EB	Dry - Warm	Poor	3,344,000	3.8 miles	No	Yes	No	Core log spreadsheet	90+
90	89	El Paso	El Paso	US 62 WB	Dry - Warm	Poor	2,415,000	4.2 miles	No	Yes	No	Core log spreadsheet	90+
91	90	El Paso	Culberson	SH 54 SB	Dry - Warm	Very Good	778,000	4.489 miles	No	Yes	No	log and pavement de	70+
92	91	El Paso	El Paso	SH 20	Dry - Warm	Poor	543,000	5.216 miles	No	Yes	No	Core log	130
93	92	Corpus Christi	Live Oak	FM 2049	Wet - Warm	Very Poor	132,000	0.5 miles	No	No	No	d analysis request D	70+
94	93	Pharr	Starr	FM 1017	Dry - Warm	Very Good	887,000	5.63 miles	No	No	No	d analysis request D	80+
95	94	Pharr	Starr	FM 1017	Dry - Warm	Very Good	887,000	4.665 miles	No	No	No	d analysis request D	70+
96	95	Lubbock	Floyd	FM 28 NB	Dry - Cold	Poor	6	1.02 miles	No	No	Yes	DCP readings	120+
97	96	Lubbock	Floyd	FM 28 NB	Dry - Cold	Poor	6	1.0 miles	No	No	Yes	DCP readings	120+
98	97	Lubbock	Floyd	FM 28 P1, P2, P3	Dry - Cold	Poor	6	900 feet	No	No	Yes	DCP readings	120+
99	98	San Antonio	Atascosa	FM 476	Dry - Warm	Good	1,222,000	8.001 miles	No	No	No	Description	70+
100	99	San Antonio	Atascosa	FM 3175	Dry - Warm	Fair	1,425,000	8.388 miles	No	No	No	Description	70+
101	100	San Antonio	Bexar	FM 1346	Dry - Warm	Fair	624,000	6.673 miles	No	No	No	Description	80+
102	101	Lufkin	Angelina	FM 1669	Wet - Warm	Fair	1,225,000	0.71	No	No	No	Description	230
103	102	Houston	Harris	FM 2553	Wet - Warm	Fair	1,910,000	0.50 miles	No	No	No	Description	230
104	103	Amarillo	Sherman	FM 1290	Dry - Cold	Fair	626,000	11.753	No	No	No	d analysis request D	70
105	104	Ft. Worth	Palo Pinto	FM 1821	Wet - Cold	Good	3,813,000	1.0 miles	No	No	No	d analysis request D	125
106	105	Ft. Worth	Palo Pinto	FM 3027	Wet - Cold	Very Good	1,809,000	1.722 miles	No	No	No	d analysis request D	60+
107	106	Atlanta	Cass	FM 2327	Wet - Cold	Good	761,000	6.0 miles	No	No	No	d analysis request D	60+
108	107	Atlanta	Titus	FM 2882	Wet - Cold	Poor	142,000	1.4 miles	No	No	No	d analysis request D	60+

	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
109	108	Atlanta	Titus	FM 21	Wet - Cold	Very Poor	152,000	1.8 miles	No	No	No	d analysis request D	60+
110	109	Atlanta	Titus	FM 71	Wet - Cold	Poor	225,000	13.6 miles	No	No	No	d analysis request D	90+
111	110	Yoakum	Wharton	FM 1299	Wet - Warm	Good	685,000	3.1 miles	No	No	No	Description	300+
112	111	Atlanta	Cass	FM 3129	Wet - Cold	Very Good	1,159,000	2.8 miles	No	No	No	d analysis request D	70
113	112	Atlanta	Cass	FM 3129	Wet - Cold	Very Good	1,159,000	1.98 miles	No	No	No	d analysis request D	70
114	113	Beaumont	Orange	FM 1135	Wet - Warm	Poor	655,000	3.9 miles	No	No	No	Description	100
115	114	Corpus Christi	San Patricio	FM 796	Wet - Warm	Very Poor	43,000	3.9 miles	No	No	No	Description	100
116	115	Houston	Waller	FM 2979	Wet - Warm	Fair	332,000	4.15 miles	No	No	No	Description	120
117	116	Houston	Waller	FM 1736	Wet - Warm	Fair	553,000	6.5 miles	No	No	No	Description	135
118	117	Austin	Lee	FM 180	Mixed	Fair	772,000	13.3 miles	No	No	No	ad analysis request &	100
119	118	Waco	Bell	FM 93	Mixed	Very Good	1,002,000	6.0 miles	No	No	No	ad analysis request &	87
120	119	Waco	Bell	FM 93	Mixed	Very Good	1,323,000	0.3 miles	No	No	No	ad analysis request &	100
121	120	Waco	Bell	FM 93	Mixed	Poor	1,165,000	0.6 miles	No	No	No	ad analysis request &	95
122	121	Waco	Bell	FM 93	Mixed	Poor	1,901,000	3.4 miles	No	No	No	ad analysis request &	200
123	122	Waco	Bell	FM 93	Mixed	Fair	1,838,000	3.75 miles	No	No	No	ad analysis request &	125
124	123	Waco	Bell	FM 439	Mixed	Good	1,719,000	2.6 miles	No	No	No	ad analysis request &	85
125	124	Waco	McLennan	FM 933	Mixed	Good	614,000	5.22 miles	No	No	No	34R LZ road analysis	85
126	125	Waco	McLennan	FM 933	Mixed	Fair	968,000	7.22 miles	No	No	No	34R LZ road analysis	90
127	126	Waco	McLennan	FM 933	Mixed	Very Good	2,243,000	5.35 miles	No	No	No	34R LZ road analysis	115
128	127	Waco	McLennan	FM 2188	Mixed	Poor	377,000	2.22 miles	No	No	No	34R LZ road analysis	105
129	128	Waco	McLennan	FM 3148	Mixed	Very Good	887,000	5.5 miles	No	No	No	34R LZ road analysis	250
130	129	Waco	McLennan	FM 308	Mixed	Very Good	1,168,000	3.05 miles	No	No	No	34R LZ road analysis	180+
131	130	Waco	McLennan	FM 107	Mixed	Good	1,513,000	6.838 miles	No	No	No	34R LZ road analysis	110
132	131	Waco	Limestone	FM 937	Mixed	Very Good	229,000	6.53 miles	No	No	No	34R LZ road analysis	215
133	132	Waco	Limestone	FM 3371	Mixed	Fair	310,000	3.35 miles	No	No	No	34R LZ road analysis	80
134	133	Waco	Limestone	FM 1633	Mixed	Very Good	510,000	9.28 miles	No	No	No	34R LZ road analysis	300
135	134	Waco	Hill	FM 310	Mixed	Good	335,000	11.85 miles	No	No	No	34R LZ road analysis	300
136	135	Waco	Hill	FM 933	Mixed	Very Good	600,000	5.82 miles	No	No	No	34R LZ road analysis	300



	A	B	C	D	E	F	J	O	T	U	V	X	Y
1	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
137	136	Waco	Hill	FM 933	Mixed	Very Good	526,000	2.90 miles	No	No	No	34R LZ road analysis	300
138	137	Waco	Hill	FM 933	Mixed	Very Good	1,687,000	2.94 miles	No	No	No	34R LZ road analysis	300
139	138	Yoakum	Jackson	FM 530	Wet-Warm	Good	150,000	18.9 miles	No	No	No	Description	300
140	139	Yoakum	Wharton	FM 1160	Wet-Warm	Good	160,000	9.804 miles	No	No	No	Description	300
141	140	Yoakum	Jackson	FM 234	Wet-Warm	Good	1,111,000	10.25 miles	No	No	No	Description	300
142	141	Waco	Hamilton	FM 1602	Wet-Warm	Very Good	159,000	9.63 miles	No	No	No	34R LZ road analysis	150
143	142	Waco	Falls	FM 712	Wet-Warm	Very Good	103,000	5.76 miles	No	No	No	34R LZ road analysis	300
144	143	Waco	Falls	FM 1671	Mixed	Good	100,000	6.03 miles	No	No	No	34R LZ road analysis	300
145	144	Waco	Bosque	FM 1637	Mixed	Very Good	326,000	4.14 miles	No	No	No	34R LZ road analysis	65
146	145	Waco	Bosque	FM 2490	Mixed	Very Good	939,000	7.93 miles	No	No	No	34R LZ road analysis	55
147	146	Waco	Bell	FM 2843	Mixed	Very Good	415,000	2.43 miles	No	No	No	34R LZ road analysis	55
148	147	Waco	Bell	FM 2843	Mixed	Very Good	415,000	8.603 miles	No	No	No	34R LZ road analysis	60
149	148	Austin	Travis	FM 734 EB	Mixed	Very Good	3,486,000	0.98 miles	No	Yes	No	Description and cores	280
150	149	Austin	Travis	FM 734 WB	Mixed	Very Good	3,486,000	0.98 miles	No	Yes	No	Description and cores	300
151	150	Austin	Travis	US 290 EB	Mixed	Very Good	9,568,000	3.558 miles	No	No	No	Description	150
152	151	Austin	Travis	FM 2304	Mixed	Good	1,827,000	0.883 miles	No	No	No	Description	80
153	152	Austin	Llano	SH 71	Mixed	Fair	1,216,000	1 mile	No	No	No	Description	85
154	153	Austin	Burnet	US 281 A	Mixed	Very Good	10,288,000	0.54 miles	No	No	No	Description	65
155	154	Austin	Burnet	US 281 B	Mixed	Good	13,132,000	0.98 miles	No	No	No	Description	65
156	155	Austin	Burnet	US 281 C	Mixed	Very Good	13,285,000	4.267 miles	No	No	No	Description	100
157	156	Wichita Falls	Wichita	FM 369	Dry-Cold	Good	949,000	1.734 miles	No	No	No	sic Investigation and	55
158	157	Austin	Travis	IH 35 R1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	sic Investigation and	75
159	158	Austin	Travis	IH 35 R2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	sic Investigation and	75
160	159	Austin	Travis	IH 35 L1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	sic Investigation and	75
161	160	Austin	Travis	IH 35 L2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	sic Investigation and	75
162	161	Austin	Travis	35 Center Lane 20	Mixed	Very Good	49,150,000	0.2 miles	No	No	No	sic Investigation and	75
163	162	Austin	Travis	35 NB Left Lane 20	Mixed	Good	49,150,000	0.3 miles	No	No	No	sic Investigation and	75
164	163	Austin	Travis	5 NB Right Lane 2	Mixed	Fair	49,150,000	0.3 miles	No	No	No	sic Investigation and	75

Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
152	Austin	Llano	SH 71	Mixed	Fair	1,216,000	1 mile	No	No	No	Description	85
153	Austin	Burnet	US 281 A	Mixed	Very Good	10,288,000	0.54 miles	No	No	No	Description	65
154	Wichita Falls	Wichita	FM 369	Dry-Cold	Good	949,000	1.734 miles	No	No	No	ic Investigation and	55
155	Austin	Travis	IH 35 R1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
156	Austin	Travis	IH 35 R2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
157	Austin	Travis	IH 35 L1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
158	Austin	Travis	IH 35 L2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
159	Austin	Travis	35 Center Lane 20	Mixed	Very Good	49,150,000	0.2 miles	No	No	No	ic Investigation and	75
160	Austin	Travis	35 NB Left Lane 20	Mixed	Good	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
161	Austin	Travis	5 NB Right Lane 2	Mixed	Fair	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
162	Austin	Travis	35 SB Left Lane 20	Mixed	Fair	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
163	Austin	Travis	5 SB Right Lane 2	Mixed	Very Good	49,150,000	0.3 miles	No	No	No	ic Investigation and	110
164	Austin	Travis	FM 973 SB	Mixed	Very Good	2,695,000	0.3 miles	No	No	No	Description	280
165	Austin	Travis	FM 973 NB	Mixed	Fair	2,695,000	0.3 miles	No	No	No	Description	120
166	Waco	Falls	SH 6 EB	Mixed	Very Good	10,636,000	6.003 miles	No	No	No	Plans	150
167	Waco	Bell	FM 2410	Mixed	Fair	789,000	1.14 miles	No	No	No	34R LZ road analysis	80
168	Waco	Bell	FM 2305	Mixed	Good	5,105,000	1.3 miles	No	No	No	34R LZ road analysis	75
169	Waco	Bell	FM 2305	Mixed	Very Good	1,556,000	3.6 miles	No	No	No	34R LZ road analysis	180
170	Waco	Bell	FM 2305	Mixed	Very Good	1,229,000	1.3 miles	No	No	No	34R LZ road analysis	120
171	Waco	Bell	FM 2271	Mixed	Very Good	1,052,000	1.949 miles	No	No	No	34R LZ road analysis	85
172	Waco	Bell	FM 1741	Mixed	Very Good	1,405,000	2.66 miles	No	No	No	34R LZ road analysis	125
173	Waco	Bell	FM 1741	Mixed	Fair	1,757,000	0.6 miles	No	No	No	34R LZ road analysis	100
174	Waco	Bell	FM 1741	Mixed	Very Good	503,000	0.9 miles	No	No	No	34R LZ road analysis	100
175	Waco	Bell	FM 1741	Mixed	Fair	253,000	1.85 miles	No	No	No	34R LZ road analysis	65
176	Waco	Bell	FM 1671	Mixed	Fair	59,000	1.07 miles	No	No	No	34R LZ road analysis	300
177	Waco	Bell	FM 485	Mixed	Good	456,000	6.24 miles	No	No	No	34R LZ road analysis	300
178	Waco	Bell	FM 437	Mixed	Good	526,000	1.946 miles	No	No	No	34R LZ road analysis	300
179	Austin	Travis	US 183 NB	Mixed	Very Good	6,116,000	2.634 miles	No	No	No	Plans	150+/-
180	Austin	Travis	US 183 SB	Mixed	Very Good	6,116,000	2.682 miles	No	No	No	Plans	135+/-

Appendix C

SCI Algorithm coding

```
Sub SCIRun()
Dim xlApp As Object
Dim xlSht As Excel.Worksheet
Set xlApp     =     CreateObject("excel.application")
Set xlSht     =     ActiveSheet
FinalRow      =     Range("B65536").End(xlUp).Row
sheetname     =     ActiveSheet.Name
Range("U3")   =     FinalRow

If (Range("ZY4").Value Or Range("ZY5").Value) Then
   Range("V23:V" & CStr(FinalRow)) = "ST"
Else
   Range("V23:V" & CStr(FinalRow)) = "AC"
End If

For i = 23 To FinalRow
district = Range("C" & CStr(i))

Select Case district
Case "Abilene", "Amarillo", "Lubbock", "Childress", "Wichita Falls"
   Range("D" & CStr(i)) = "Dry-Cold"
Case "Austin", "Brownwood", "Waco", "Bryan"
   Range("D" & CStr(i)) = "Mixed"
Case "Fort Worth", "Dallas", "Paris", "Atlanta", "Tyler"
   Range("D" & CStr(i)) = "Wet-Cold"
Case "Corpus Christi", "Yoakum", "Houston", "Beaumont", "Lufkin"
   Range("D" & CStr(i)) = "Wet-Warm"
Case "El Paso", "Odessa", "San Angelo", "San Antonio", "Laredo", "Pharr"
   Range("D" & CStr(i)) = "Dry-Warm"
End Select

Next i

For i = 23 To FinalRow
   For j = 1 To 7
   Cells(i, 22 + j) = Round((9000 * 25.4 * Cells(i, 13 + j).Value) / (Cells(i, 13)), 2)
   Next j
Next i

For i = 23 To FinalRow
   Cells(i, 30) = Round(0.33 * 0.24 * Cells(i, 13) / ((Cells(i, 20) / 1000) * 72), 2)
   'AASHTO MR
   Cells(i, 31) = Round(1.5 * 25.4 * Cells(i, 7).Value, 2)
```

```
Next i

    i = 23
    While i >= 2 And i <= FinalRow 'Offset for every row
    'Calculate offset
    Cells(1, 100) = 0
    Cells(2, 100) = 305
    Cells(3, 100) = 610
    Cells(4, 100) = 914
    Cells(5, 100) = 1219
    Cells(6, 100) = 1524
    Cells(7, 100) = 1829
    For j = 1 To 7
        Cells(j, 101) = Abs(Cells(i, 31) - Cells(j, 100))
        Cells(j, 102) = Cells(i, 22 + j)
    Next j
    j = 0

    k = 7
    While k > 0
        Range("CW1:CW" & CStr(k)).Select
        minval = xlApp.WorksheetFunction.Min(xlSht.Range("CW1:CW" & CStr(k)))
        For mincount = 1 To k
            If Range("CW" & CStr(mincount)).Value = minval Then
                minrow = mincount
                Exit For
            End If
        Next mincount
        Range("CV" & minrow & ":CX" & minrow).Select
        Selection.Cut
        Range("CY" & 8 - k & ":DA" & 8 - k).Select
        ActiveSheet.Paste
        Range("CV" & minrow & ":CX" & minrow).Select
        Selection.Delete Shift:=xlUp
        k = k - 1
    Wend
    Range("CY1:DA7").Select
    Selection.Cut
    Range("CV1:CX7").Select
    ActiveSheet.Paste

    Ra = Cells(1, 100)
    Rb = Cells(2, 100)
```

```
   Rc = Cells(3, 100)
   Rab = Ra - Rb
   Rac = Ra - Rc
   Rba = Rb - Ra
   Rbc = Rb - Rc
   Rca = Rc - Ra
   Rcb = Rc - Rb
   Rxa = Cells(i, 31) - Ra
   Rxb = Cells(i, 31) - Rb
   Rxc = Cells(i, 31) - Rc
   Da = Cells(1, 102)
   Db = Cells(2, 102)
   Dc = Cells(3, 102)
   Cells(i, 32) = Round(((Rxb * Rxc * Da) / (Rab * Rac)) + ((Rxa * Rxc * Db) / (Rba
*Rbc)) + ((Rxa * Rxb * Dc) / (Rca * Rcb)), 2)
   i = i + 1
   Wend

Range("CV1:CX7").Select
Selection.Delete Shift:=xlUp
Range("AC2").Select

For i = 23 To FinalRow
   Cells(i, 33) = Round(Cells(i, 23) - Cells(i, 32), 2)  'W1-W1.5Hp
   If (Cells(i, 22) = "AC") Then
      k1 = 0.4728
      k2 = -0.481
      k3 = 0.7581
   Else
'   If (Cells(i, 12) = "ST") Then
      k1 = 0.1165
      k2 = -0.3248
      k3 = 0.8241
   End If
   Cells(i, 34) = Round(k1 * Cells(i, 33) ^ k2 * (25.4 * Cells(i, 7)) ^ k3, 2)
   Cells(i, 35) = Round(SNreq(Cells(i, 21), Cells(i, 30)), 2)
   Cells(i, 36) = Round(Cells(i, 34) / Cells(i, 35), 2)
Next i

Range("AJ23:AJ" & CStr(FinalRow)).Select
Selection.NumberFormat = "0.00"

ActiveSheet.Shapes.AddChart.Select
```

```
ActiveChart.ChartType = xlLineMarkersStacked
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(1).Values = "='" + sheetname + "'!$AJ$23:$AJ$"
+CStr(FinalRow)
ActiveChart.SeriesCollection(1).XValues = "='" + sheetname + "'!$F$23:$F$"
+CStr(FinalRow)
ActiveChart.Legend.Select
Selection.Delete
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.Axes(xlCategory).AxisTitle.Select
ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "TRM"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.Axes(xlValue).AxisTitle.Select
ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "Structural Condition Index
(SCI)"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.ChartTitle.Text = " SCI vs TRM Plot"


ActiveSheet.Shapes.AddChart.Select
ActiveChart.ChartType = xlLineMarkersStacked
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(1).Values = "='" + sheetname + "'!$AJ$23:$AJ$"
+CStr(FinalRow)
ActiveChart.SeriesCollection(1).XValues = "='" + sheetname + "'!$E$23:$E$"
+CStr(FinalRow)
ActiveChart.Legend.Select
Selection.Delete
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.Axes(xlCategory).AxisTitle.Select
ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "FWD Stations"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.Axes(xlValue).AxisTitle.Select
ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "Structural Condition
Index(SCI)"

ActiveChart.ChartArea.Select
```

```
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.ChartTitle.Text = " SCI vs FWD Stations Plot"
End Sub

Function SNreq(ByVal X As Double, ByVal Y As Double) As Double

n = Range("ZX4").Value
For i = (11 * (n - 1) + 6) To (11 * (n - 1) + 10)
minval = Sheets("SNReq").Cells(i, 4)
If Y >= minval Then yindex = i Else Exit For
Next i

For j = 6 To 10
minval = Sheets("SNReq").Cells((11 * (n - 1) + 4), j)
If X >= minval Then xindex = j Else Exit For
Next j

SNreq = Sheets("SNReq").Cells(yindex, xindex)

End Function
```

Appendix D

SCI Algorithm User Manual

Project 5-4322
SCI Algorithm Tool: A User's Manual 5-4322-01
IMPLEMENTATION OF A NETWORK-LEVEL PAVEMENT STRUCTURAL CONDITION INDEX BASED ON FALLING WEIGHT DEFLECTOMETER DATA

This document provides User manual of the Structural Condition Index (SCI) Algorithm Tool developed under the Project 5-4322-01: Implementation of a Network-Level Structural Condition Index Based on Falling Weight Deflectometer Data. This user manual is prepared so as to address Task 7 of assisting TxDOT in implementing the SCI.

1.1 Introduction To The Tool

The user manual for SCI Algorithm tool is prepared so that the necessary material to assist TxDOT is provided with the implementation of the SCI upon completion of validating and testing the SCI. The tool is an interface between SCI methodology and the users. The SCI Algorithm tool allows the user to input the required data, run the algorithm and view SCI analysis results for any pavement section. This user manual will specifically address the new SCI index and give necessary guidelines on how it can be used to evaluate the condition of a roadway. This manual will further provide background in FWD testing and analysis concepts for network-level applications.

2. Important features of the Tool

2.1 System Requirements

To use the SCI Algorithm, Microsoft Office should be installed in the computer. The algorithm was written in macro enabled excel using Visual Basic Applications (VBA). Visual Basic for Applications, Excel's powerful built-in programming language, permits to easily incorporate user-written functions into a spreadsheet.

2.2 Programming Structure

The SCI algorithm is stored in a module in a workbook called as "SCI Analysis Workbook". This workbook has to be saved in the user's computer as macro enabled excel workbook to run the analysis. The workbook contains a total of four worksheets as shown in Figure 1. They are Example SCI Analysis, SCI Analysis Module, SNReq and Drop Down Box inputs.

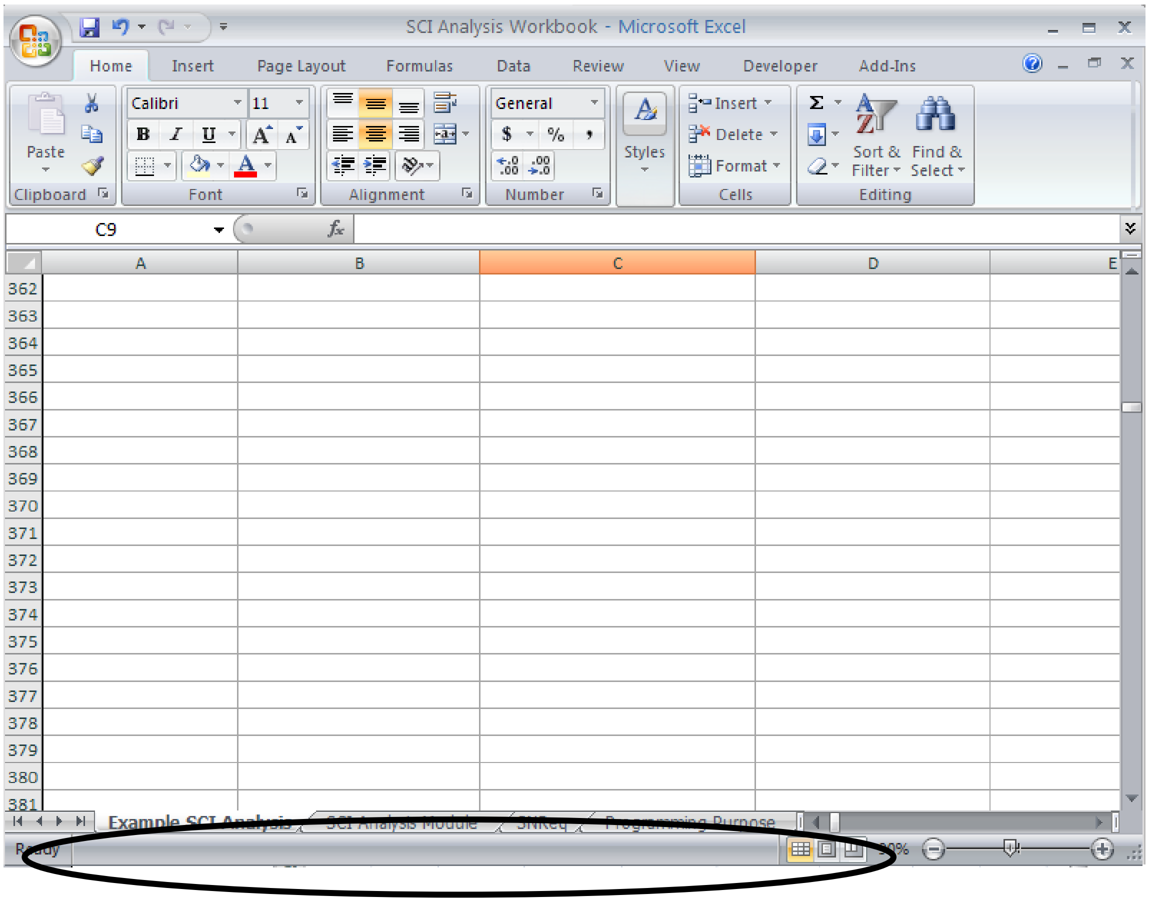


Figure 1: “SCI Analysis Workbook “-Macro Enabled Excel Workbook

2.3 Tab 1: Example SCI Analysis

The first worksheet is the “Example SCI Analysis” worksheet used for demonstration purpose in the SCI Analysis workbook. This worksheet acts as a quick reference for the user to understand how the inputs are to be specified in the rest of workbook for new sections for SCI analysis. The units for inputs are mentioned in the headings for inputs. The code has been written in such a way that the SCI analysis works well only with certain units for inputs to be used in the workbook. It is required that the input data be in the correct units to avoid debug problems later.

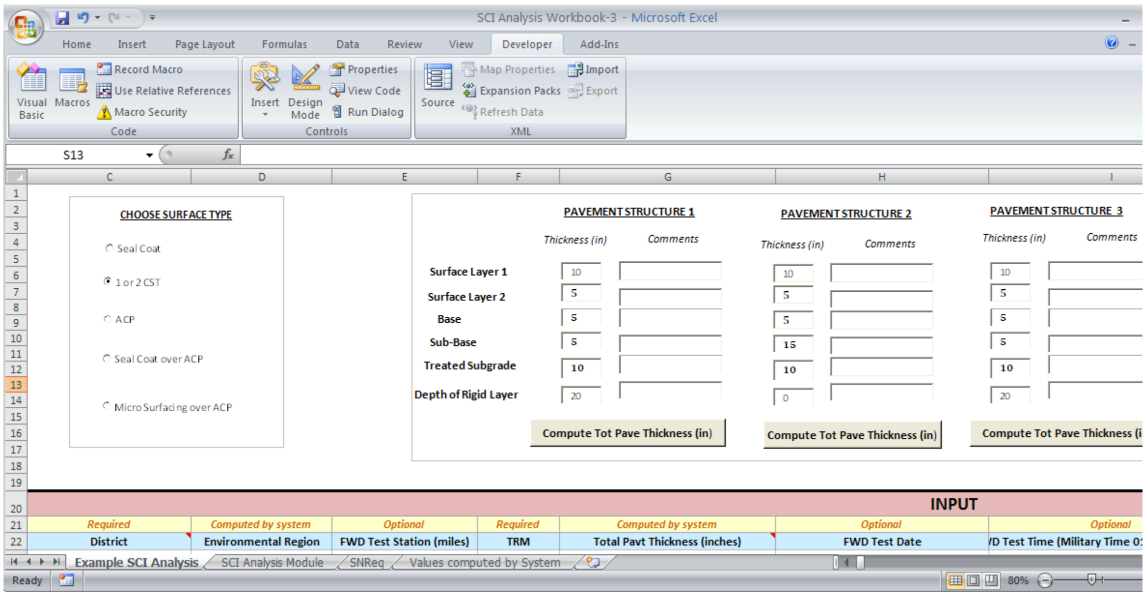


Figure 2: Input Data

The input data and output data are separated. All the input data is not necessary. Hence, input data is labeled as either required or optional. Data like environmental region is computed by the tool and hence the environmental region is labeled as computed by system.

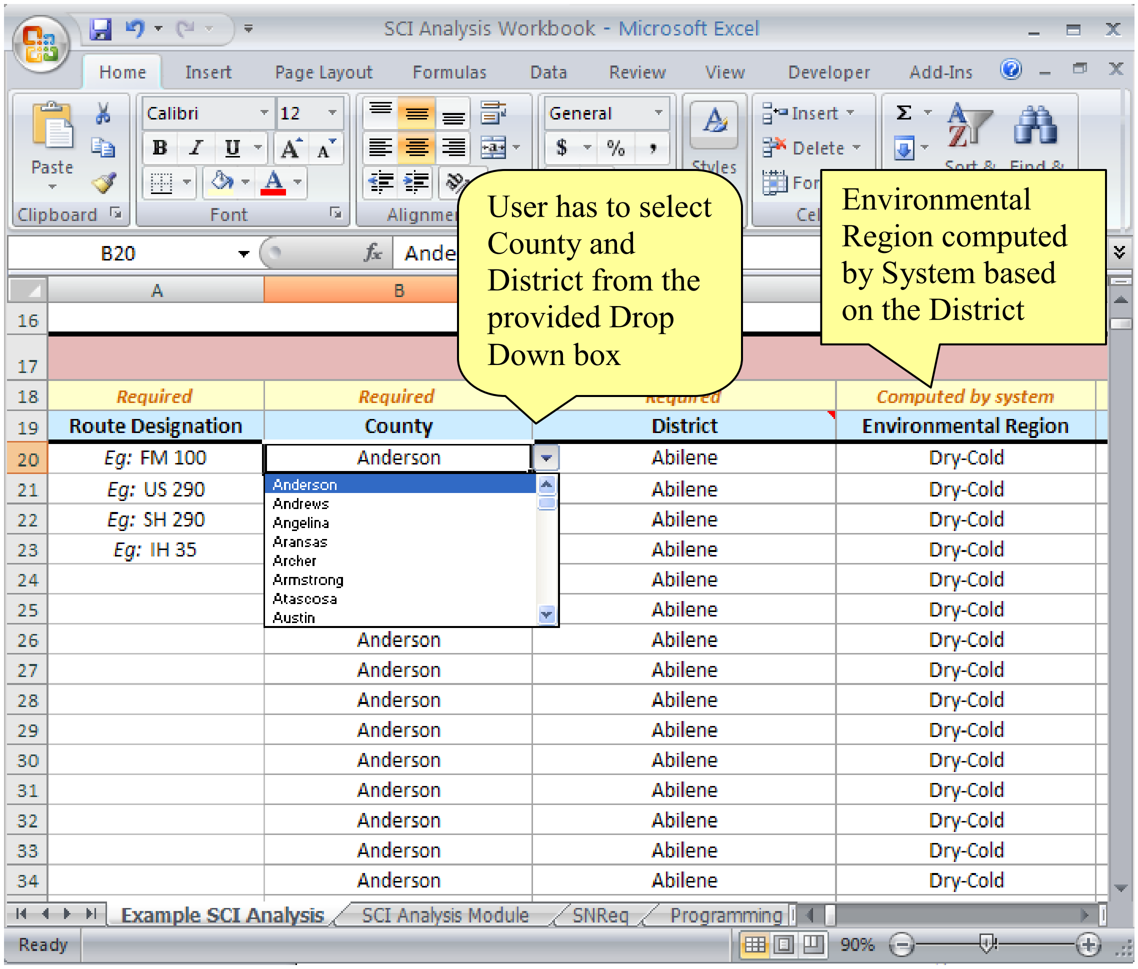


Figure 3: Input Data

The Column A of a pavement section is the Route Designation. The user needs to specify the route, for e.g. Column A as either FM 100 or US 290 or SH 290 or IH 35. The Column B and Column C are the County and District. Texas has a total of 254 counties, 25 Districts and five environmental zones. The user has to select the county and district for the provided drop down box. The tool processes the district data to get the appropriate environmental region in Column D for the selected county.

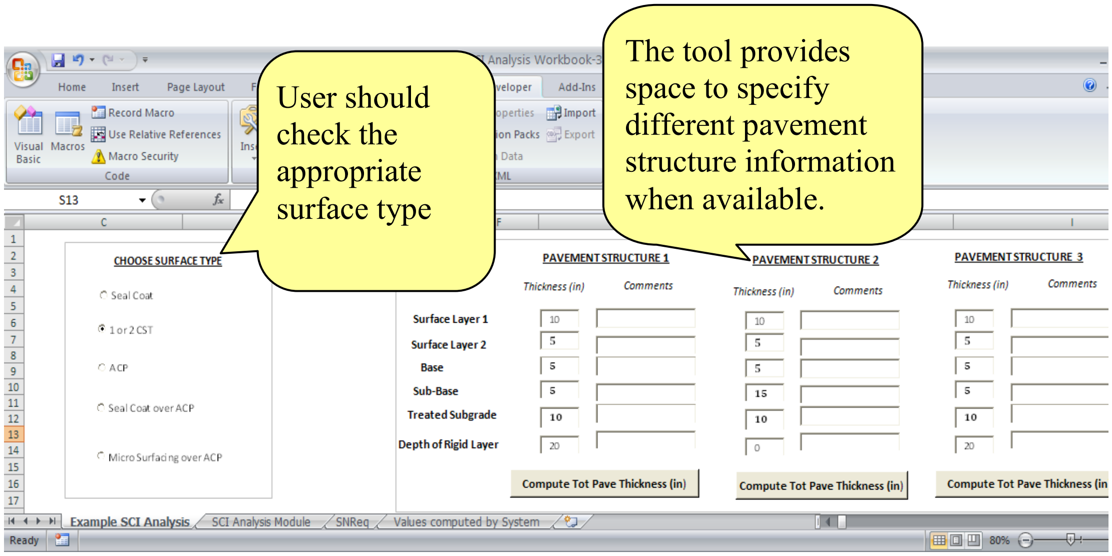
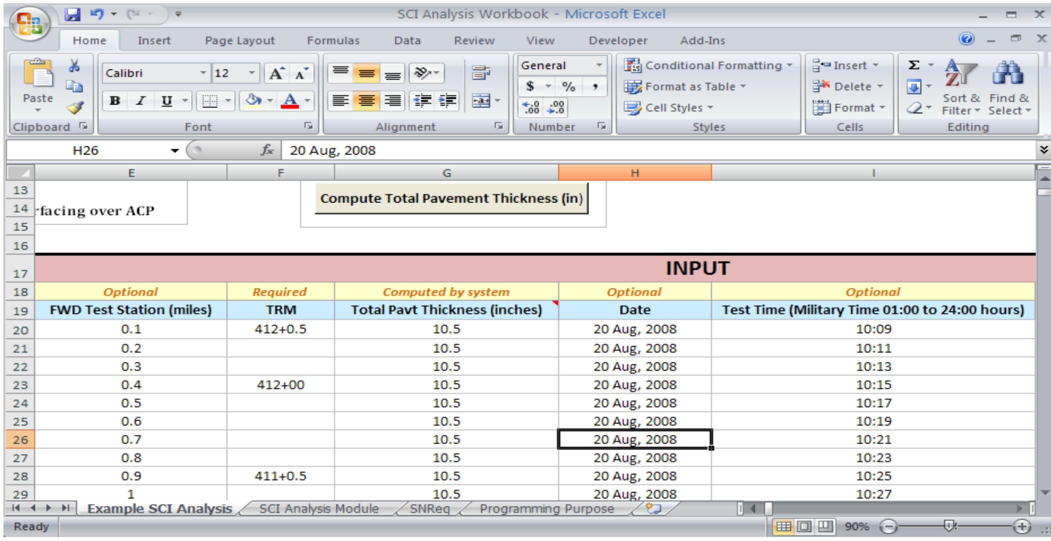


Figure 4: Surface Type and Pavement Structure Data

Surface Type can be either as Surface Treatment or Asphalt Concrete. The user can chose the appropriate surface type by choosing the right box out of the given five options. The next step is to input the Pavement thickness information. A route may comprise of more than one pavement structure. In this tool, a total of five pavement structure thickness information can be recorded. The user should select the cell, and then has to click on "Compute Tot Pavement Thickness (in) "under Pavement Structure 1. Similarly, the user has to select the corresponding TRM –thickness cell at that point where the pavement structure 2 begins before clicking on "Compute Tot Pavement Thickness (in) "under Pavement Structure 2. It is required that user fills the layer thickness information including '0' inches of any layer to avoid debug problems later.



Optional	Required	Computed by system	Optional	Optional
FWD Test Station (miles)	TRM	Total Pavt Thickness (inches)	Date	Test Time (Military Time 01:00 to 24:00 hours)
0.1	412+0.5	10.5	20 Aug, 2008	10:09
0.2		10.5	20 Aug, 2008	10:11
0.3		10.5	20 Aug, 2008	10:13
0.4	412+00	10.5	20 Aug, 2008	10:15
0.5		10.5	20 Aug, 2008	10:17
0.6		10.5	20 Aug, 2008	10:19
0.7		10.5	20 Aug, 2008	10:21
0.8		10.5	20 Aug, 2008	10:23
0.9	411+0.5	10.5	20 Aug, 2008	10:25
1		10.5	20 Aug, 2008	10:27

Figure 5: Input Data

Column E is the FWD Test Station in miles and Column F is to specify Texas Reference Marker (TRM) for identifying the location. Total Pavement thickness is the thickness of better materials above the natural or prepared sub-grade. The computed thickness is stored in Column G. The user has the option of providing Date and FWD Test Time in Military hours in Column H and Column I.

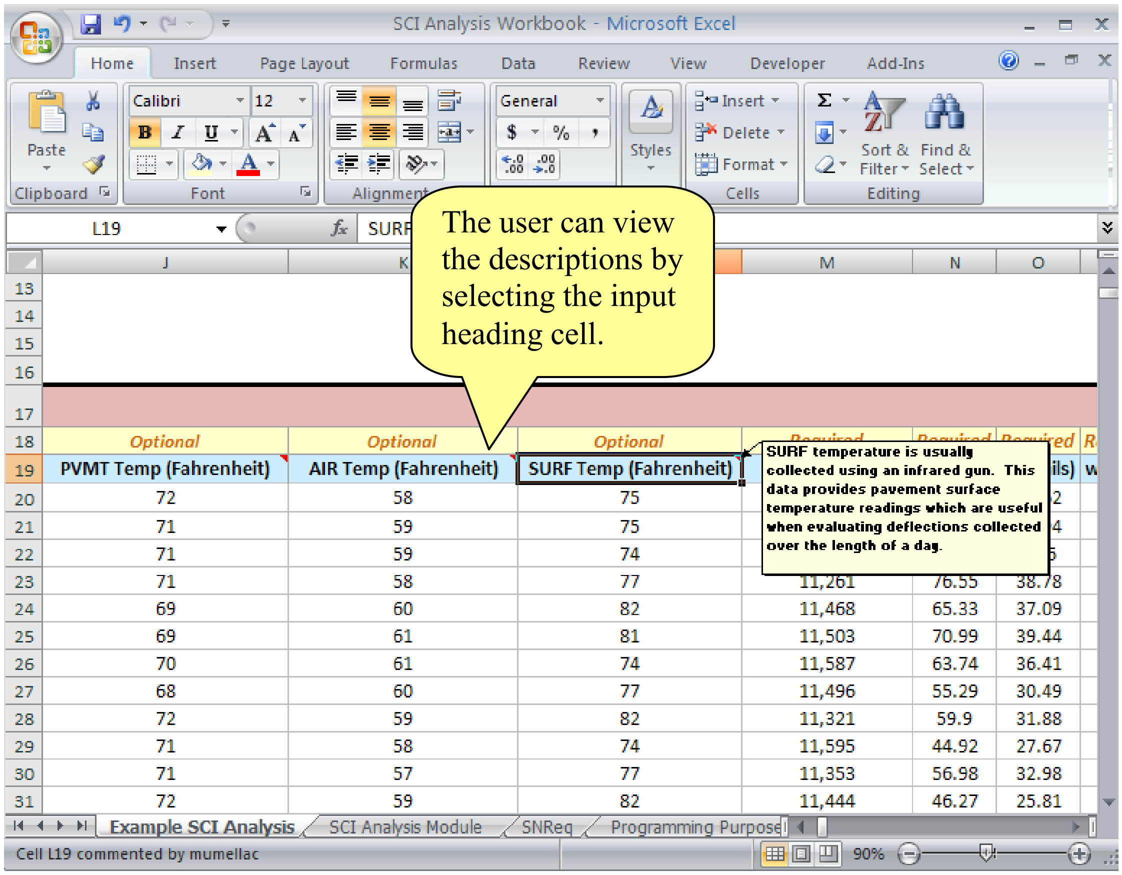


Figure 6: Optional Input Data

Pavement Temperature, Air Temperature; Surface Temperature in Fahrenheit is to be noted down in Columns J, K and L respectively. At this time, the SCI methodology does not take temperature into account for the analysis. Columns for FWD testing time and temperatures have been provided so as to facilitate temperature corrections of SCI in the future. The tool also provides descriptions of Pavement Temperature, Air Temperature and Surface Temperature.

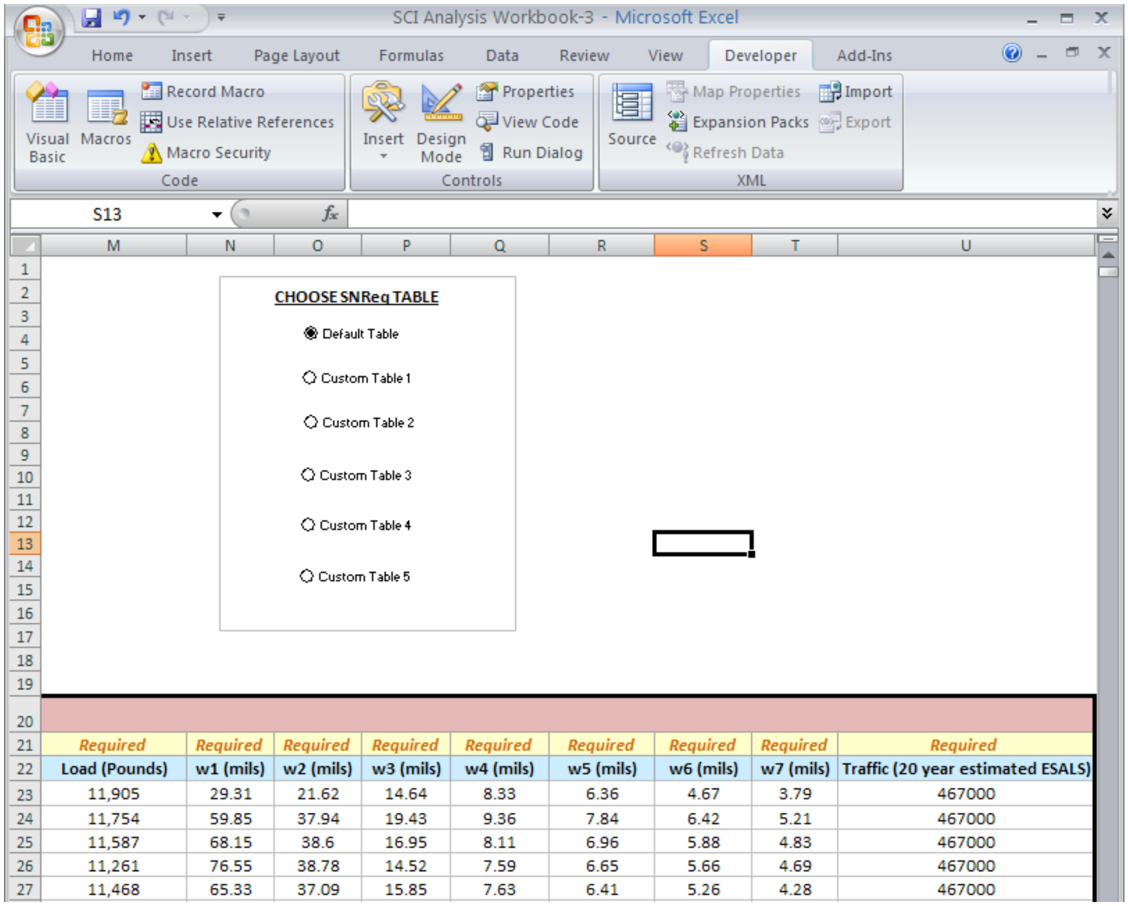


Figure 7: Choosing SNReq Table

The user is provided with the option of choosing SNReq Table. The current SCI Analysis is based on the values taken from the default table. More details about the SNReq Table are given in Section 2.5. The load at which Falling Weight Deflectometer (FWD) are recorded is in Column M. The recorded FWD reading in mils for seven sensors are to be inputted in Column N to Column T. Column U includes the estimated 20 year ESALS traffic.

2.4 Tab 2: SCI Analysis Module

Based on the reference worksheet "Example SCI Analysis", the user can now input the data in "SCI Analysis Module". The user has to carefully follow the instructions and specifications mentioned in the "Example SCI Analysis" to work with new data in "SCI Analysis Module".

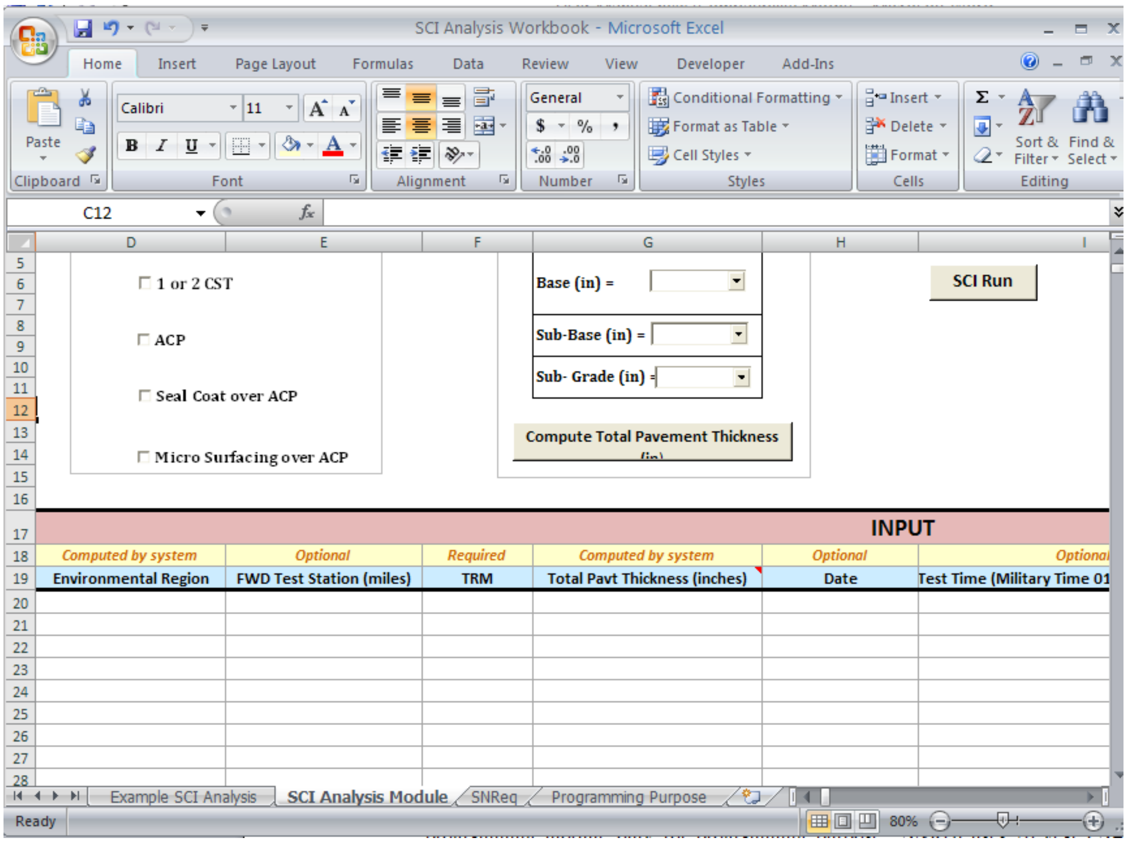
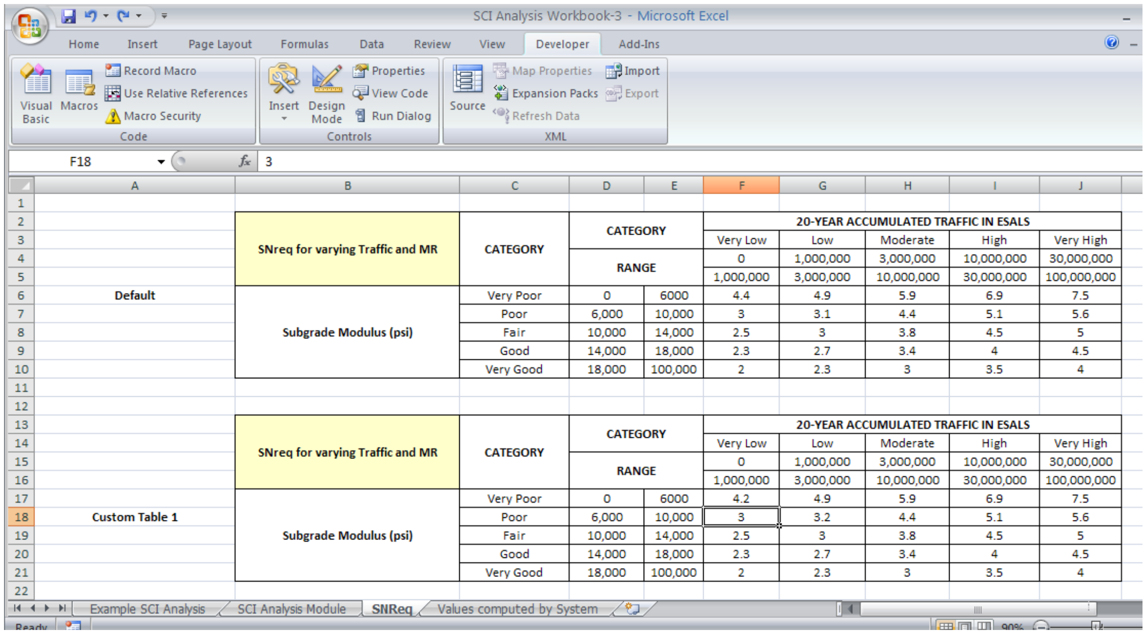


Figure 8: Sheet 2-"SCI Analysis Module"

2.5 Tab 3: SNReq

Within the workbook, "SNReq" worksheet is included as a database for the programming module only for the SCI Algorithm applications. SNReq uses 20 year ESALS traffic and Sub grade modulus as part of the SCI analysis. This worksheet further gives an understanding of the new ranges for traffic and sub grade modulus that are used in SCI analysis. This tool also provides the flexibility of choosing between different custom SNReq tables. The user can input SNReq data in the custom tables and view the analysis results. However, it is to be noted that current SCI analysis is based on the values taken from the default table.



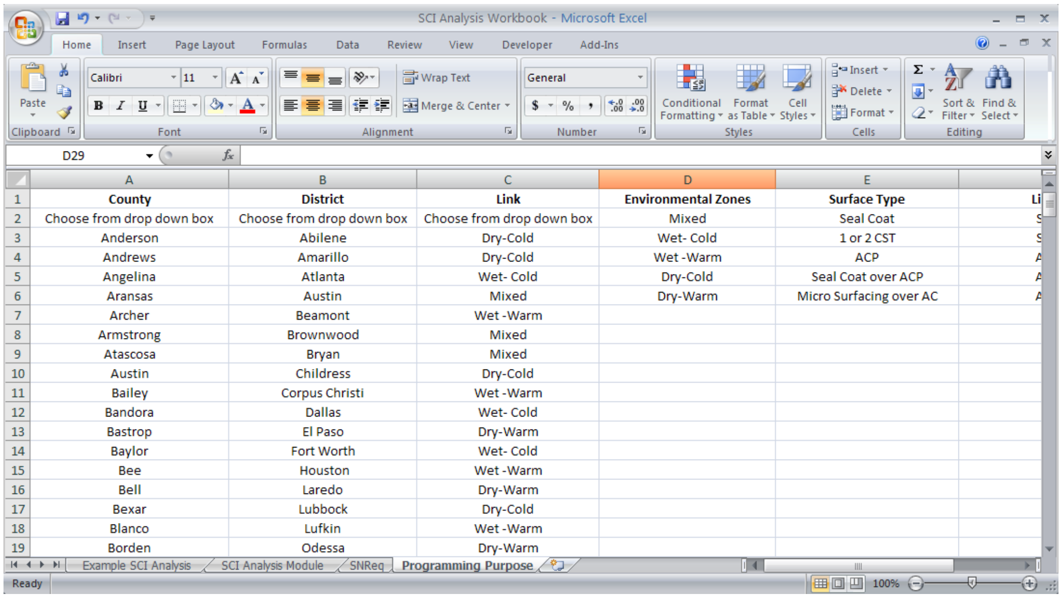
	SNreq for varying Traffic and MR	CATEGORY	CATEGORY RANGE		20-YEAR ACCUMULATED TRAFFIC IN ESALS				
					Very Low	Low	Moderate	High	Very High
					0	1,000,000	3,000,000	10,000,000	30,000,000
					1,000,000	3,000,000	10,000,000	30,000,000	100,000,000
Default	Subgrade Modulus (psi)	Very Poor	0	6000	4.4	4.9	5.9	6.9	7.5
		Poor	6,000	10,000	3	3.1	4.4	5.1	5.6
		Fair	10,000	14,000	2.5	3	3.8	4.5	5
		Good	14,000	18,000	2.3	2.7	3.4	4	4.5
		Very Good	18,000	100,000	2	2.3	3	3.5	4

	SNreq for varying Traffic and MR	CATEGORY	CATEGORY RANGE		20-YEAR ACCUMULATED TRAFFIC IN ESALS				
					Very Low	Low	Moderate	High	Very High
					0	1,000,000	3,000,000	10,000,000	30,000,000
					1,000,000	3,000,000	10,000,000	30,000,000	100,000,000
Custom Table 1	Subgrade Modulus (psi)	Very Poor	0	6000	4.2	4.9	5.9	6.9	7.5
		Poor	6,000	10,000	3	3.2	4.4	5.1	5.6
		Fair	10,000	14,000	2.5	3	3.8	4.5	5
		Good	14,000	18,000	2.3	2.7	3.4	4	4.5
		Very Good	18,000	100,000	2	2.3	3	3.5	4

Figure 9: Sheet 3-“SNReq”

2.6 Tab 4: Inputs for Drop Down Boxes

The last sheet in the workbook is the Sheet 4 used only for Drop Down Box inputs. The sheet gives overview of the counties, districts in Texas. It further gives idea of how each district has been linked with environmental regions. Similarly, this worksheet further tells how the each of the five surface type descriptions has been linked with Surface Type to be used in SCI Analysis.



	A	B	C	D	E	
1	County	District	Link	Environmental Zones	Surface Type	Li
2	Choose from drop down box	Choose from drop down box	Choose from drop down box	Mixed	Seal Coat	S
3	Anderson	Abilene	Dry-Cold	Wet- Cold	1 or 2 CST	S
4	Andrews	Amarillo	Dry-Cold	Wet -Warm	ACP	A
5	Angelina	Atlanta	Wet- Cold	Dry-Cold	Seal Coat over ACP	A
6	Aransas	Austin	Mixed	Dry-Warm	Micro Surfacing over AC	A
7	Archer	Beamont	Wet -Warm			
8	Armstrong	Brownwood	Mixed			
9	Atascosa	Bryan	Mixed			
10	Austin	Childress	Dry-Cold			
11	Bailey	Corpus Christi	Wet -Warm			
12	Bandora	Dallas	Wet- Cold			
13	Bastrop	El Paso	Dry-Warm			
14	Baylor	Fort Worth	Wet- Cold			
15	Bee	Houston	Wet -Warm			
16	Bell	Laredo	Dry-Warm			
17	Bexar	Lubbock	Dry-Cold			
18	Blanco	Lufkin	Wet -Warm			
19	Borden	Odessa	Dry-Warm			

Figure 10: Sheet 4-"Hard-wired input values for drop down boxes"

3. Using the tool

This section explains how to use the tool from a user's perspective. A hypothetical project named as "SCI Analysis Workbook" has been used for demonstration purpose.

3.1 Location of the tool

The first step in the process is to locate the "SCI Analysis Workbook" excel macro enabled workbook from the computer.

3.2 Security Settings

SCI algorithm requires that the macro settings are enabled in workbook. To do this, the user needs to go to Office button-Excel Options- Trust Center- Enable all macros-OK (Figure 5). Else, a security question might pop up.

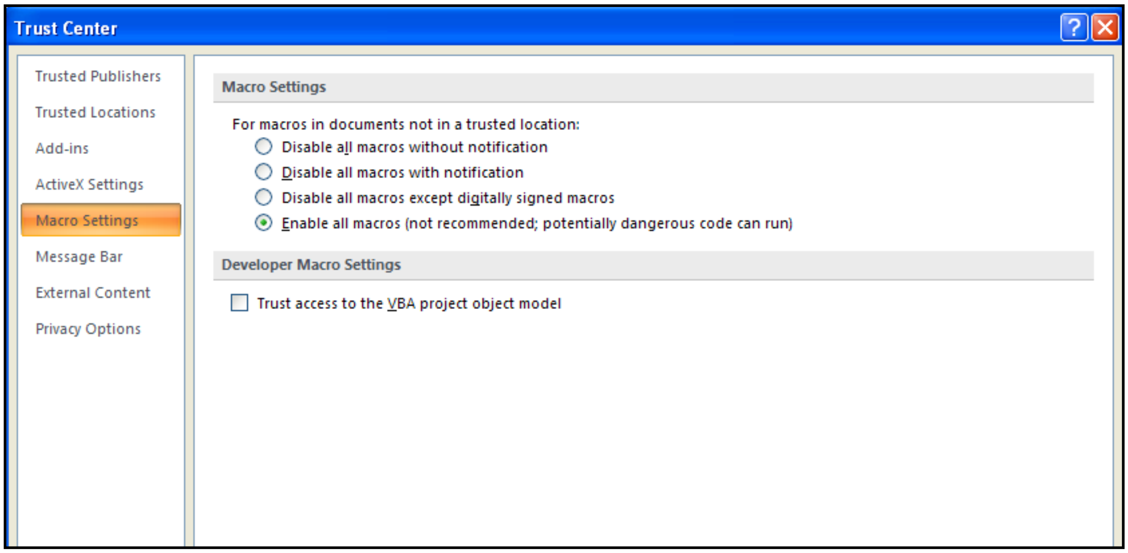


Figure 11: Macro Settings

3.3 Input Data

The user has to input the following data as explained in a new worksheet in the respective columns with correct units. The SCI Algorithm can handle any number of stations in the input data and the user should not worry about the number of rows. The user should make sure that the input data captioned as "required" is to be inputted for SCI algorithm tool.

3.4 Running the Algorithm

The algorithm has been written in the form of macro which has been assigned to a button called as "SCI Run" in the worksheet. A right click on the button will run the analysis.

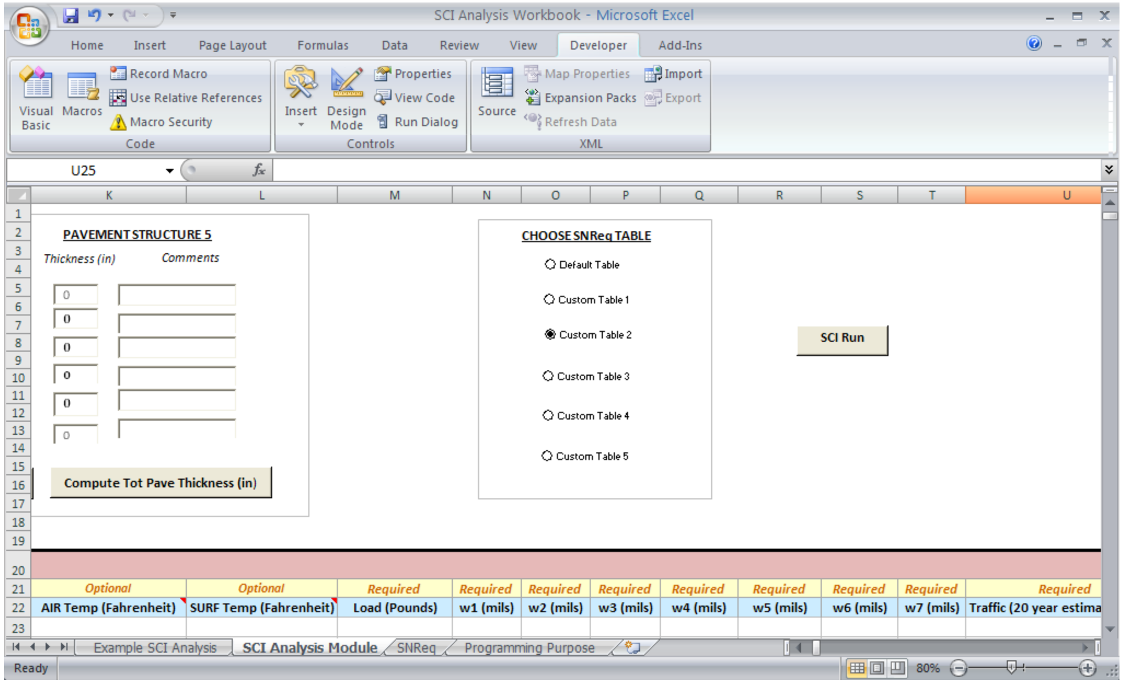


Figure 12: Running SCI Algorithm

3.5 SCI Analysis Results

The final output, Structural Condition Index (SCI) is reported under Column AJ as in Figure 8. The user can further view the normalized deflections, AASHTO calculated Subgrade Modulus (M_R), Effective Structural Number (SN_{eff}) and Required Structural Number (SN_{req}) in the worksheet which are part of intermediate steps to obtain the Structural Condition Index. The tool automatically generates graphs for SCI vs TRM as well as SCI vs FWD Stations.

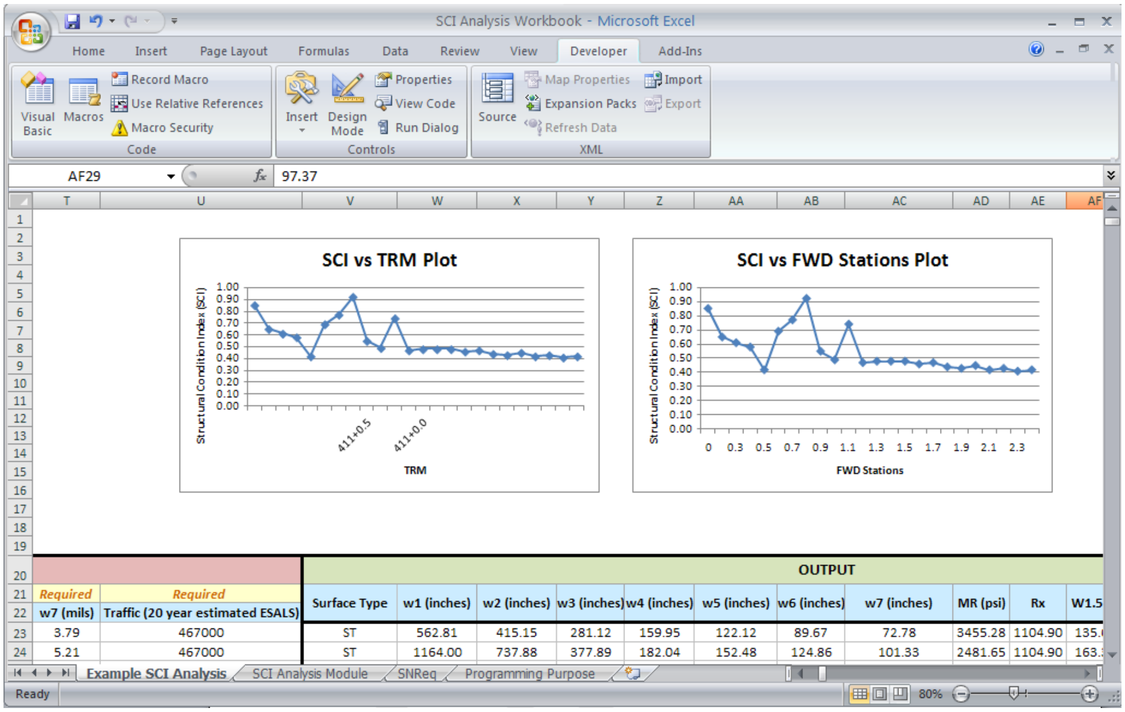


Figure 13: SCI Analysis Results

4. Guidelines for Maintenance and Rehabilitation (M&R) Options

A survey analysis has been conducted as part of the Project 5-4322-01 by taking expert opinions with regard to Structural Condition Index (SCI) Threshold Analysis. This exercise involved selecting the appropriate PMIS treatment level for the traffic, pavement conditions, SCI, soil conditions and other factors given. The results obtained from the SCI Threshold Analysis as in Figure 14 formed the basis to establish guidelines for Maintenance and Rehabilitation (M&R) options. However, the survey results of PMIS treatment level varied quite a bit within the experts and average of the results was taken to establish a brief guideline about the PMIS treatment level based on SCI. Hence, it is to be noted that the suggested PMIS treatment levels in Table 2 only act as a guideline at network level and not as cut off point at project level.

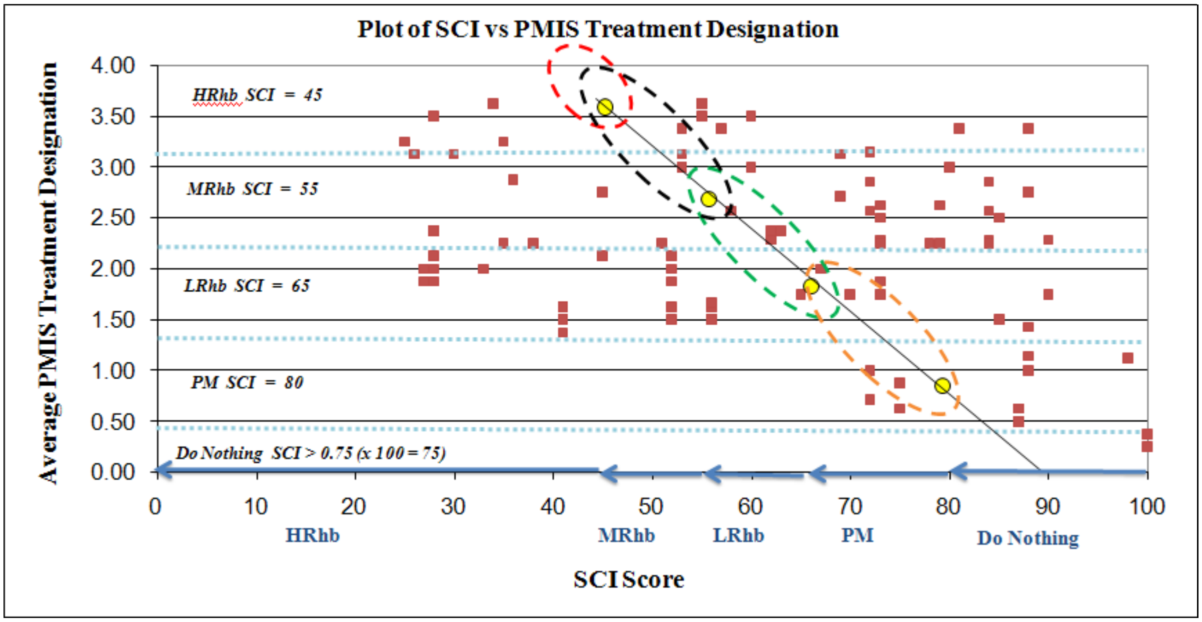


Figure 14: Survey Results of PMIS Treatment Levels with Structural Condition Index (SCI)

Table 2: Guidelines for PMIS Treatment Level based on SCI

SCI	PMIS Treatment Level
<0.45	HRhb
0.45-0.55	MRhb
0.55-0.65	LRhb
0.65-0.80	PM
>0.80	Do Nothing

5. Falling Weight Deflectometer (FWD)

Falling Weight Deflectometer readings are obtained through load produced by dropping weight measured by seven sensors located at typical offsets of 12 inches. The recorded pavement deflections in response to applied pulse load will result in deflection basin. The test sections obtained for the implementation study included short sections of 1000’ with tests performed every 25’ +/-; long routes up to 19 miles in length with consistent test spacing on 100’ or 500’ intervals as well as other route lengths and test spacing. The interval at which FWD data was collected varied from section to section depending on the purpose of testing. For some projects, FWD measurements were recorded for every 50 feet, whereas for others, FWD measurements were taken at 0.5 miles intervals. It is very well known that conducting more FWD tests will yield more accurate results about pavement section, however, economic constraints of implementation makes it essential that ideal testing frequency needs to be found out. Research further suggests that appropriate time for FWD deflection testing for various regions of the state needs to be identified.

5.1 FWD Deflection Testing Interval

In the research done under the Project 5-4322-01, the number of test points necessary to provide a sufficient data to characterize the section was assessed using Cumulative Difference Approach (CDA). The Cumulative Difference Approach (CDA) suggested by American Association of State Highway Transportation Officials **(**AASHTO) is a graphical method, which facilitates the detection of homogeneous sections through segmentation analysis. The analysis was conducted by comparison of segmentation results of original and reduced data through 0.25 mile spacing’s. The results obtained through Cumulative Difference Approach (CDA) method suggests that FWD spacing of 0.25 mile spacing is the ideal FWD spacing for SCI analysis. Moreover, PMIS scores are also recorded at 2 points per 0.5 mile. Thus, it is recommended that users follow FWD spacing of 0.25 mile as it can be used in conjunction with PMIS scores as shown in Figure 10.

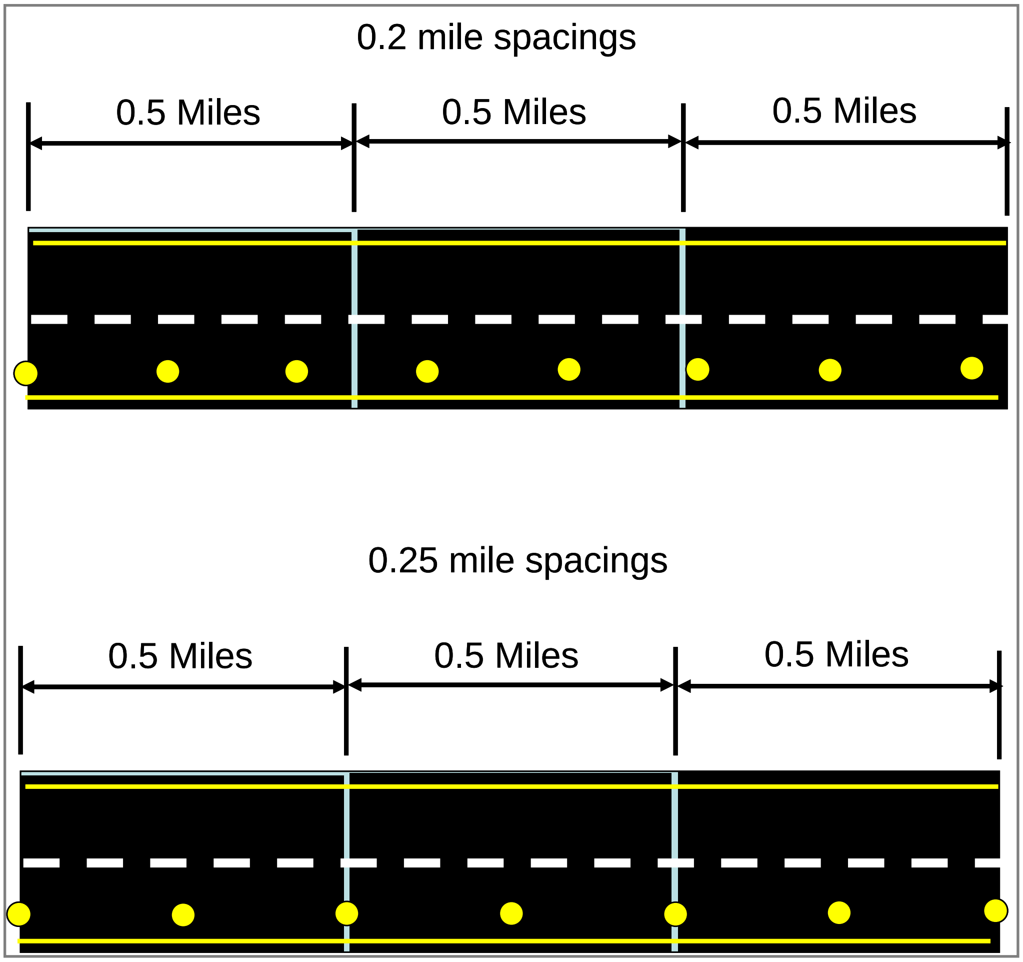


Figure 15: FWD Testing Interval

5.2 FWD Deflection Testing time

It is observed based on the literature review that FWD readings are affected by lot of parameters, one out of which are seasonal variations in any region. Significant seasonal variations usually affect pavement strength determined through FWD deflections. Such FWD deflections might misinterpret true pavement's condition. As such, most of the researchers suggest that deflection testing should be discouraged during winter months when the sub-grade and base may be frozen. The magnitude of variation and the ideal time for deflection testing has been established by setting up different experiments across the country as well as Texas by different researchers.

Literature review suggests that FWD testing should be performed during the season of the year when permanent deformations (non-linear behavior) is most likely to occur. Generally, the worst pavement condition could either be in the hottest or wettest part of the year. The research done by Poehl and Scrivner in 1971 to determine ideal FWD data collection in Texas indicates that the annual rainfall affects the timing of annual maximum deflection observed at a point in Texas than the annual temperatures. Poehl and Scrivner found that the above average deflections occur in spring in East Texas, and above average deflections occur in summer in West Texas. Also, the annual percentage change in deflections (max-min) was usually greater in the eastern part (wet part) of Texas, than in the western (dry part). Hence, it is recommended that users follow the seasons to do FWD deflection testing as shown in Figure 16.

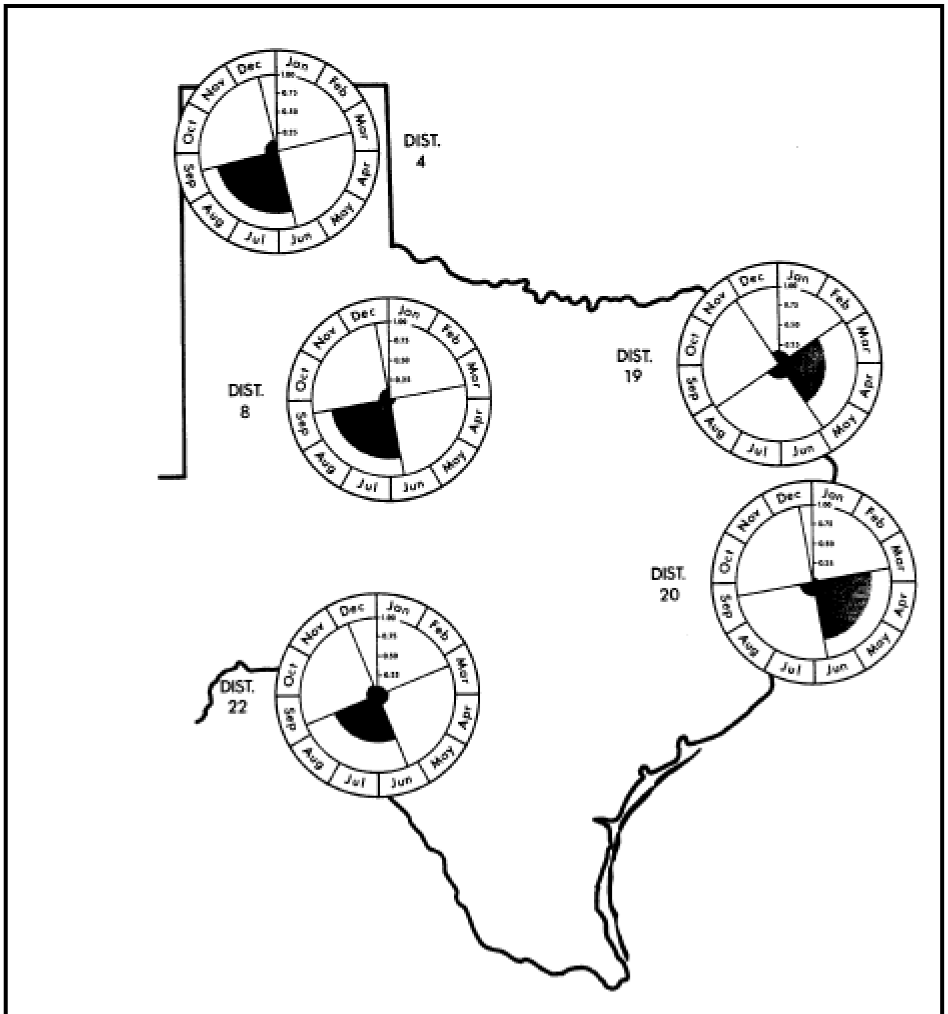


FIGURE 16 - Data from Table 10 plotted on annual clocks. Radii of shaded segments are proportional to probability of occurrence of above-average deflections.

Figure 16: Highest Deflections in Texas with season

The results obtained from this review have been linked up with Texas environmental zones to give user more flexibility. The table summarizes the recommended FWD deflection testing times based on Texas environmental zones.

Table 3: Guidelines for FWD Deflection Testing Time based on Environmental zones

Environmental Region	FWD Deflection Testing Time
Dry-Cold	Mid June-Mid September
Wet-Cold	March-May
Mixed	Mid June-Mid September/ March-May
Dry-Warm	Mid June-Mid September
Wet-Warm	Mid March-Mid June

6. Summary

The development of SCI Algorithm tool had three basic objectives: assist TxDOT with the implementation of SCI, evaluation of the condition of a roadway using the new SCI index and to provide background in FWD deflection testing and analysis concepts. It is important that the user has macro enabled excel workbook and follows the data base structure: Units and Inputs as indicated in the user manual for effective SCI analysis. By establishing guidelines about PMIS treatment levels in relation to SCI, the manual addresses how SCI can be used to evaluate the condition of a roadway. Ideal FWD deflection interval as well as deflection testing times to extract the accurate information about a pavement's condition has been provided for the users. Some recommendations for improving SCI Algorithm tool have been suggested.

- The suggested representative value of the section in the Project is based on Cumulative Difference Approach (CDA). Inclusion of an automated process of segmentation in SCI algorithm can greatly help.
- The SCI Algorithm provides space for inputting FWD Time and Three Temperature data: Pavement, Air and Surface. By possible inclusion of temperature correction of SCI in the future, the efficiency of SCI algorithm can be made improved.

- FWD Parsing Code can be used in SCI Algorithm so that the user can browse files and directly take values form the raw FWD file to work with SCI Algorithm in future.

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